DOE/CH/10435-01

RESEARCH AND DEVELOPMENT OF PROTON-EXCHANGE-MEMBRANE (PEM) FUEL CELL SYSTEM FOR TRANSPORTATION APPLICATIONS

INITIAL CONCEPTUAL DESIGN REPORT

CONTRACT NO. DE-AC02-90CH10435

FEBRUARY 1994

PREPARED FOR:

U.S. DEPARTMENT OF ENERGY
OFFICE OF TRANSPORTATION TECHNOLOGIES

PREPARED BY:

ALLISON GAS TURBINE DIVISION
GENERAL MOTORS CORPORATION
INDIANAPOLIS, IN 46206

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FOREWORD

This report documents a portion of the work performed by General Motors Corporation under contract DE-AC02-90CH10435, Research and Development of Proton-Exchange Membrane (PEM) Fuel Cell System for Transportation Applications. The overall intent of the first phase of this program is to produce a methanol-fueled 10-kW power source demonstrating system feasibility, and to develop an initial evaluation of an electrochemical engine (ECE) in transportation applications.

Specifically, this report describes the conceptual design studies which were conducted to define the initial propulsion system specifications for a PEM fuel cell powered vehicle (FCV) and to establish a prioritization of future research and development requirements. Major achievements include the development of an ECE power source model and its integration into a comprehensive power source vehicle model; establishment of candidate FCV mission requirements; initial FCV studies; and a candidate FCV recommendation for further study.

General Motors (GM) has addressed this "Electrochemical Engine Transportation Application Program" with a team that draws on:

- the system integration capabilities and multiple advanced power system design disciplines and expertise in place at the Allison Gas Turbine Division (Allison)

- the substantial experience, membrane and electrode research capability, hybrid electric vehicle, and electrical power train system technology, hardware, and test vehicle resources that were developed under GM funding as background to this project and are in place at GM's North American Operations Research and Development (NAO R&D) Center

- the catalyst experience, ceramic and metal monolith support, fuel metering hardware, and research and development (sensors, etc) resources developed under GM funding as part of this project and in place at GM's AC Rochester Division

- the infrastructure of expertise and resources in place in the fuel cell stack and membrane and electrode industries and the working relationship between those industries and Allison

- the unique capabilities and resources existing at Los Alamos National Laboratory (LANL) at which Allison has established an ECE Joint Development Center staffed by both Allison and LANL personnel

In this arrangement, Allison served as the prime contractor. The fuel cell stack subcontractor was Ballad Power Systems, while Dow Chemical Company supplied membranes and electrodes. The preparation of this report represents a joint effort between Allison, LANL, and NAO R&D Vehicle Systems Research Department (GMVS), with significant input from The Analytical Sciences Corporation (TASC) and DAKO Services.

This work was funded by the U.S. Department of Energy (DOE), Energy Efficiency and Renewable Energy, Office of Transportation Technologies, Office of Propulsion Systems, Electric/Hybrid Propulsion Division. Project and technical management was provided by DOE's Electric/Hybrid Propulsion Division with technical oversight and advice provided from Argonne National Laboratory under the direction of Mr. Clinton C. Christianson, Manager, Power Source Technology, Chemical Technology Division. Dr. Howard Creveling and Dr. Robert Sutton of Allison Gas Turbine Division of General Motors were the Program Manager and the Technical Director, respectively, for this project.

Dr. Pandit G. Patil
Office of Transportation Technologies
U.S. Department of Energy

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Allison Gas Turbine (Allison) Division of General Motors (GM) Corporation has successfully completed Tasks 1.1 and 1.2 of Task 1.0 - System Conceptual Design Study, segments of Research and Development of Proton Exchange Membrane (PEM) Fuel Cell Systems for Transportation Applications, sponsored by the U.S. Department of Energy (DOE). The major achievements of Tasks 1.1 and 1.2 include the development of an electrochemical engine power source model and the integration of that model into a comprehensive power source/hybrid electric vehicle propulsion model, establishment of candidate PEM fuel cell powered electric vehicle (FCV) mission requirements, FCV studies, and a candidate FCV recommendation for further study. This document is the draft Initial Conceptual Design Report (ICDR) due at the end of Task 1.2.

VEHICLE TYPE, MISSION/PERFORMANCE REQUIREMENTS

In order to satisfy customer expectations, future FCVs are projected to be required to equal or exceed the performance, operating convenience, and functionality of current products. Vehicle use and driving patterns of this study are, therefore, consistent with those estimated from previous DOE studies for current vehicles. Realistic design and performance requirements for an FCV are, consequently, based on review of available information on current products, their trends and projections, and expert opinion. Candidate FCVs modeled include several sizes of passenger cars, an urban transit bus, and mini-vans (Environmental Protection Agency [EPA] two-wheel drive special purpose vehicle class). GM North American Operations Research and Development Center (NAO R&D) Vehicle Systems Research Department (GMVS) defined the vans and passenger cars to be approximate averages of several typical GM and other manufacturers' vehicles, while the bus matched that used in the DOE Fuel Cell/Battery Powered Bus Systems report.[1]

FCV CONFIGURATION

A PEM ECE/battery electric series power train was used to evaluate the various vehicular candidates. Power train components included an ECE, advanced lead acid batteries, and a state-of-the-art electric drive system. As used in this report, the term ECE includes all major subsystems of the fuel cell power plant, i.e. fuel cell stack, fuel processor, water/thermal and control management systems, and compressor/expander as described in Section IV. Power train packaging considered component function, size, mass distribution, and general safety assumptions.

FCV SIMULATION AND EVALUATION

The various candidate vehicles were analyzed using existing GM proprietary simulation tools (in some cases modified to accommodate the ECE) and other techniques developed specifically under Task 1.1 - Model Development and Application. These tools permit the estimation of vehicle performance and energy consumption during various driving scenarios. The FCVs were assumed to be operated on methanol, current passenger vehicles on gasoline, and current buses on diesel fuel. Fuel economy is based on volume of fuel consumed; however, as methanol has less energy per unit mass or volume than petroleum derived fuels, a fuel economy comparison only masks the relative energy utilization of the different vehicles. Therefore, energy consumption (kW-hr/km) is also included to permit an equitable basis to compare projected FCVs to current vehicles.

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[1]DOE Report DOE/CH/10650-01, *Research and Development of Fuel Cell/Battery Powered Bus Systems, Phase 1 Final Technical Report*, prepared by Booz, Allen, and Hamilton, Transportation Consulting Division, Bethesda, MD, February 1990 under DOE contract DE-AC08-87NV10650.

Because the start-up time of the ECE is estimated to be longer than that of its internal combustion engine (ICE) counterpart, two different types of FCVs were analyzed. The "maximum performance" FCV can achieve the 0 to 96.6 km/hr acceleration time of the comparison conventional vehicle, while the ECE is in the start-up mode. The "similar performance" FCV is required only to meet the acceleration demands of the Federal Urban Driving Schedule (FUDS) during the ECE start-up mode. The FCVs differ in the amount of batteries that are carried onboard; consequently, the maximum performance FCV also requires a larger ECE because of the additional weight of the larger battery pack.

The FCV passenger car power train components are packaged to meet both levels of vehicle performance without power train intrusion into the passenger compartment. FCVs with maximum performance capability are estimated, as described above, to be heavier and have smaller trunk/cargo areas than their conventional counterparts. Energy consumption is lower despite projected weight penalties; but fuel economy, as defined in this report, and highway range are marginally less because of the change in fuels.

The PEM ECE powered urban transit bus seating capacity and fuel consumption are estimated to be superior to those of the phosphoric acid fuel cell (PAFC) ECE powered bus of a previous DOE report. However, both of the ECE buses are projected to have fewer seats than a conventional diesel powered bus. Fuel consumption of the PEM ECE powered bus is estimated to be marginally less than that of a comparable diesel bus, while the fuel consumption of the PAFC ECE powered bus is projected to be slightly greater.

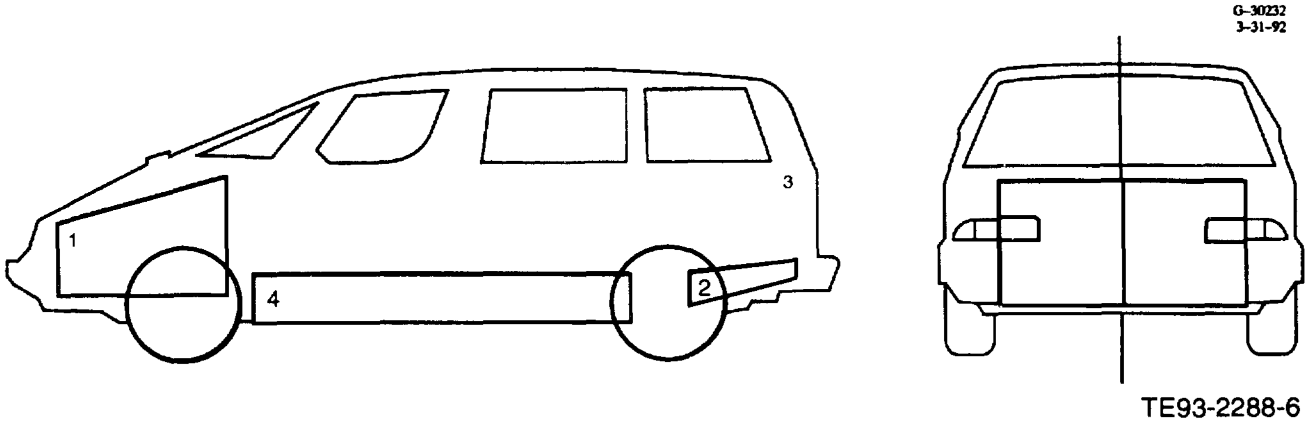
CONCLUSIONS AND RECOMMENDATIONS

Each of the projected FCV candidates was ranked in order of its ability to meet or exceed established vehicle requirements. Then a composite score was computed based on the objective ranking. Based on this analysis, an FCV mini-van with performance *similar* to that of current mini-vans is recommended for further trade-off analysis studies. Acceleration is slightly less than that of the current production mini-van during the ECE start-up time, but FCV performance is equivalent to that of the current production mini-van after the ECE was warmed-up and fully operational. No reduction in passenger or trunk/cargo space for packaging of the power train components is anticipated. The fuel economy (miles per gallon of methanol) of the FCV is slightly less than that of an equivalent conventional gasoline-powered ICE production baseline model, but its composite energy usage is estimated to be only 51% of that of the current production mini-van. Specifications for the current production and projected similar performance FCV mini-van are presented in Tables 1-I and 1-II, respectively.

The second choice for further analysis is also an FCV mini-van, but with performance equivalent to a current production vehicle when the ECE is cold. Again, no reduction in passenger or trunk/cargo space for packaging of the power train is anticipated. The energy usage for this projected FCV is estimated to be 57% of that of the equivalent current production mini-van.

The third choice for further analysis is a similar performance FCV compact vehicle (EPA compact class). Acceleration is slightly less than that of the current production compact car during the ECE start-up time, but is equivalent to that of the current production compact car after the ECE is warmed-up and fully operational. In this case, some reduction in trunk/cargo space for packaging of the power train is anticipated. The energy usage, however, is estimated to be only 49% of that of an equivalent current production compact vehicle.

Table 1-I.
Current production mini-van vehicle.



Vehicle Data

EPA classification	Mini-Van
Vehicle type	Chevrolet APV
Curb weight (kg/lb)	1,498/3,295
Test weight (kg/lb)	1,634/3,595
Wheelbase (cm/in.)	279/109.8
Overall length (cm/in.)	493/194.2
Overall width (cm/in.)	188/73.9
Frontal area (m^2/ft^2)	2.72/29.3
Drag coefficient (C_d)	0.33
Number of passengers	7

Performance

Top speed (km/hr/mph)	169/105
0 to 96.6km/hr (60 mph)(sec)	cold 12.2
	warm 12.2
Gradeability (% grade)	
Short-term max. negotiable	30.0%
Long-term @ 96.6 km/hr	>6%
Range on FHDS (km/mi)	740/460
Start-up & drive away time	<1 Sec
Long-term storage (days)	
Ambient-normal start (21°C/70°F)	35

EPA Volume Available

Passenger (m^3/ft^3)	4.15/146.5
Trunk/cargo (m^3/ft^3)	0.521/18.4
Total volume (m^3/ft^3)	4.67/164.9
Fuel tank size (L/gal)	75.7/20.0

Energy Usage

Fuel economy (gasoline)	
FHDS-highway (km/L/mpg)	9.80/23.0
FUDS-city (km/L/mpg)	7.63/18.0
Composite energy (55/45) usage (kW-hr/km)	1.053

Components

	Rated power (kW)	Weight (kg/lb)	Volume (m^3/ft^3)	Location
Battery pack	NA	NA	NA	NA
Electric drive system	NA	NA	NA	NA
Electrochemical engine	NA	NA	NA	NA
ICE and transmission	90	314/692	0.235/8.3	1
Fuel tank (filled)	NA	68/150	0.076/2.7	2

NA = not applicable

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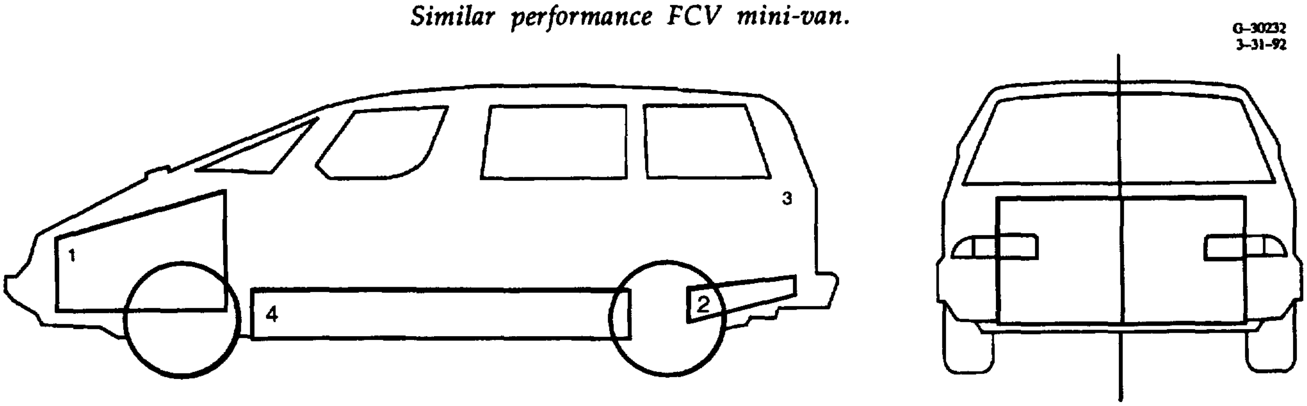
Table 1-II.
Similar performance FCV mini-van.



Vehicle Data		Performance	
EPA classification	Mini-Van	Top speed (km/hr / mph)	145/90
Vehicle type	Conceptual FCV	0 to 96.6km/hr (60 mph)(sec)	cold 19.3
Curb weight (kg/lb)	1,805/3,972		warm 11.6
Test weight (kg/lb)	1,942/4,272	Gradeability (% grade)	
Wheelbase (cm/in.)	279/109.8	Short-term max. negotiable	15.1%
Overall length (cm/in.)	493/194.2	Long-term @ 96.6 km/hr	>6%
Overall width (cm/in.)	188/73.9	Range on FHDS (km/mi)	692/430
Frontal area (m^2/ft^2)	2.72/29.3	Start-up & drive away time	<1 Sec
Drag coefficient (C_d)	0.33	Long-term storage (days)	
Number of passengers	7	Ambient-normal start (21°C/70°F)	NA

EPA Volume Available		Energy Usage	
Passenger (m^3/ft^3)	4.15/146.5	Fuel economy (gasoline)	
Trunk/cargo (m^3/ft^3)	0.521/18.4	FHDS-highway (km/L/mpg)	9.09/19.5
Total volume (m^3/ft^3)	4.67/164.9	FUDS-city (km/L/mpg)	7.52/15.5
Fuel tank size (L/gal)	75.7/20.0	Composite energy (55/45) usage (kW-hr/km)	0.536
		Energy usage compared to ICE	51%

Components

	Rated power (kW)	Weight (kg/lb)	Volume (m^3/ft^3)	Location
Battery pack	67	291/641	0.136/4.8	4
Electric drive system	180	110/243	0.192/6.7	1
Electrochemical engine	60	244/537	0.365/12.9	4
ICE and transmission	NA	NA	NA	NA
Fuel tank (filled)	NA	72/158	0.076/2.7	2

NA = not applicable

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II. INTRODUCTION

This ICDR documents a portion of the work performed under Task 1.0 - System Conceptual Design Study on the DOE sponsored Research and Development of PEM Fuel Cell System for Transportation Applications program. The overall purpose of this entire Task is to develop one or more conceptual designs of a full-scale PEM ECE propulsion system in order to:

- define the preliminary ECE propulsion system and FCV configuration, size, mass, and performance characteristics
- establish the ECE propulsion system component specifications
- conduct an assessment of the various issues associated with the commercialization of fuel cell propulsion technology in transportation applications (issues considered include environmental aspects, ECE propulsion system economics as applied to the transportation arena, and alternative fuel availability, economy of use, purity, and toxicity)
- define and prioritize future R&D requirements

This work is being conducted by a team directed by GM, with significant activities underway at Allison (which serves as the prime contractor), at GMVS located at NAO R&D, and with several subcontractors (TASC, DAKO Services, and Sobey and Associates). The DOE sponsors this work under contract DE-AC02-90CH10435.

GOALS AND OBJECTIVES OF THIS REPORT

This ICDR represents results from one of three ongoing studies being conducted under Task 1.0. Task 1.0 is subdivided into four separate tasks as defined by the Work Breakdown Structure (WBS) presented in the Program Management Plan (EDR 15105) approved by DOE on March 1, 1992.

These four (4) separate subtasks are:

- Task 1.1 Model Development and Application
  - Power Source Model
  - Integration of Power Source Model with Electric Vehicle Propulsion Model
- Task 1.2 Mission Definition
  - Requirements
  - Initial Vehicle Application Studies
  - Vehicle Recommendations and *Initial Conceptual Design Report* - Report 1
- Task 1.3 Trade-off Analysis
  - Power train Component Requirements
  - Sizing and Packaging Studies
  - Trade-off Studies
  - Identification and Prioritization of Future R&D Needs
  - *Reference Power train Design and Trade-off Analysis Report* - Report 2
- Task 1.4 *Commercialization Study of Fuel Cell Propulsion Transportation Applications* - Report 3
  - 1.4.1 Environmental Issues and Trends in Regulations
  - 1.4.2 Fuel Cell Propulsion Transportation Economics

- Identification of Transportation Areas Applicable to Fuel Cell Usage
  - Preliminary Competitive Analysis
- 1.4.3 Fuel Issues
  - Availability
  - Economics of Development
  - Storage and Distribution
  - Purity and Toxicity/Environmental Concerns
  - Specification of Candidate Fuel

Results and recommendations from Task 1.1 and 1.2 are contained within this ICDR. Effort on Task 1.3 will commence following the DOE Technical Manager's approval of the recommendation contained within this report. Some generic work regarding the development of a reference power train design has already been initiated. The commercialization study of Task 1.4 is an ongoing effort. The results of Task 1.3 and 1.4 will be presented in two separate additional reports prior to the end of this Phase I program effort.

APPROACH USED FOR INITIAL CONCEPTUAL DESIGN REPORT

The major achievements of Task 1.1 and 1.2 include:

- development of an ECE power source model
- integration of that model into a comprehensive power source/FCV propulsion model
- establishment of candidate FCV mission requirements
- FCV studies
- recommendation of a candidate FCV for further study

As defined in this report, an FCV consists of a series connected ECE and advanced batteries with a state-of-the-art electric drive system. The ECE includes all major subsystems of the fuel cell system power plant, e.g., fuel cell stacks, fuel processor operating on methanol, ancillaries including a turbo-compressor/turboexpander unit, heat exchangers, pumps, etc, and controls for the entire system that provide thermal and water management systems and respond to power management requests from the vehicle controller. The ECE power source is described in detail in Section IV.

In order to satisfy customer expectations, future FCVs are projected to be required to equal or exceed the performance, operating convenience, and functionality of current products. Power train packaging considers component function, size, mass distribution, and general safety assumptions. Vehicle use and driving patterns are, therefore, consistent with those estimated from previous DOE studies for current vehicles.

Specifically, Task 1.1 involved development of a sophisticated power source modeling code and integration of that code into detailed electric vehicle propulsion models. Joint Development Center (JDC) personnel successfully expanded an original LANL code and have modeled the ECE operation at predetermined power levels for fixed physical system parameters. The ECE model has been updated and modified for use on VAX, HP, and Apple Macintosh computer systems. The ECE modeling code is a chemical engineering system model that solves for steady-state solutions of energy and mass flows in an operating ECE system. The model is structured to obtain engineering assessments that project ECE component mass, volume, power production, flow rates, temperatures, pressures, and mole fractions throughout the ECE system. Input parameters require that details of some components, such as the polarization curve for the fuel cell stack, be specified. However, the modeling code also calculates details of other components such as heat exchangers. One important result to date of this code has been to identify the particular physical arrangement that optimizes system thermal integration, especially the recovery of waste heat from the fuel cell stack that can be effectively used in the fuel processing operation.

Per the program plan, candidate FCVs modeled include several sizes of passenger cars, an urban transit bus, and multipurpose vans. GMVS defined the vans and passenger cars to be approximate averages of several typical GM and other manufacturer's vehicles, while the bus matched that used in the DOE's Fuel Cell/Battery Powered Bus Systems report. Based upon ECE/battery characteristics described later in this report and an envelope of desired vehicle performance requirements, ECE system design specifications were determined to require at least three levels of continuously operating power production, 45-kW, 60-kW, and 80-kW electrical energy output. Calculations to define ECE optimal configuration and operating parameters for power levels of 45-kW, 60-kW, and 80-kW were completed. The current density and voltage at these power levels were selected as 1100 mA/cm^2 at 0.7V per cell. This represents goal conditions; such performance has recently been demonstrated by a PEM fuel cell at the JDC using a new Dow membrane. Full power conditions are specified as 2200 mA/cm^2 at 0.5V, resulting in nearly a 150% intermittent peak power operating condition.

All of the objectives set forth in the program plan have been incorporated into the ECE system model, except for the pollution emission calculations. It was determined that prediction of low level emissions is highly dependent upon the combustor/catalytic converter design being utilized. Addition of these computations will be implemented when experimental results from the Mark III combustor are available. In all other aspects, key design issues were investigated and the power source design was optimized for use in the integrated model.

Finally, the ECE power source system operating conditions were mapped as a matrixed set of three-dimensional (3-D) data algorithms. A series of steady-state operational conditions were calculated, 3-D maps of steady-state performance delineated, and required operational routes that move between these operational plateaus determined. These ECE system data algorithms were then integrated into more general electric vehicle simulation models developed by GMVS. Combining the two codes permits vehicle requirements and power plant operating conditions to be determined over a given driving cycle. Integration of the ECE power source and electric vehicle simulation model represents the main effort of Task 1.1. The GM electric vehicle simulation model is oriented towards power train and vehicle requirements and contains sophisticated electrical control and battery/motor simulation options with advanced vehicle dynamics descriptions. The simulation model itself is considered proprietary by GM but results obtained through its use were used to satisfy the requirements of Task 1.2.

The final version of this integrated model yields projected system performance, fuel efficiency, and detailed system operating conditions (current densities, reactant inlet and exit temperatures, fuel and oxidant usages, battery state-of-charge, etc) of the power source and power train components in candidate vehicles over a driving cycle. In combination with design analysis, results from the model are used to verify preliminary sizing and packaging concepts of the total propulsion system and drive train components and to determine the effect of power plant installation on vehicle design and performance. Modeling and simulation of the overall system are carried out as appropriate to ensure that the system requirements unique to this transportation application are addressed and its R&D needs identified and prioritized. The full capabilities of the integrated model, combined with an estimated analysis of response to power changes, and start-up and shut-down times will be utilized later in Task 1.3 for preparation of the Reference Power train Design and Trade-off Analysis Report.

In Task 1.2, TASC, DAKO, and GMVS conducted an initial evaluation of the propulsion power source/drivetrain requirements for three transportation applications: passenger cars, vans, and an urban transit bus. The initial assessment of the mission definition, power, and power train requirements for each of these vehicles was conducted during the development of the integrated computer model. As soon as the integrated computer code was developed it was used to do more sophisticated vehicle application studies. Because the computer model yields power plant fuel consumption and operational characteristics as a function of vehicle and mission requirements, the passenger cars, vans, and urban transit bus were then modeled to investigate performance requirements over established driving cycles. The FCVs were assumed to be operating on methanol and comparisons were made to current passenger cars operating on gasoline and current buses on diesel fuel. Because the start-up time of the ECE is projected to be longer than that of its ICE counterpart, two different types of FCVs were considered. A "maximum performance" FCV can match the 0 to 96.6 km/hr acceleration time of a comparison conventional vehicle when the ECE is in a start-up mode. A "similar performance" FCV, on the other hand, is required to meet only the acceleration requirements of the FUDS while the ECE is in start-up mode. The vehicles differ in the amount of batteries that are carried onboard. Consequently, the maximum performance FCV also requires a larger ECE due to the additional weight of the larger battery pack.

The initial calculations predicted preliminary power train subsystem and component sizes based on performance requirements over a prescribed driving cycle. The validity of the computations was then determined through simulation of each of the three vehicle types while considering technical constraints set by the ECE system vehicle packaging requirements. These vehicle simulation analyses refined and/or verified preliminary recommended combinations of ECE and battery power based on optimization of performance, range, energy usage, and various other factors.

The above analyses resulted in preliminary estimates of vehicle and ECE/battery power plant size, fuel consumption, and initial ECE cost for each of the three vehicle types. Subsequently, one vehicle design is recommended for further consideration by the DOE Technical Manager.

III. VEHICLE AND MISSION DEFINITIONS

As part of WBS Task 1.2 TASC, DAKO, and GMVS conducted an initial evaluation of the propulsion power source/drivetrain requirements for three transportation applications: passenger cars (of various size), vans, and an urban transit bus. The initial assessment of the mission definition, power, and power train requirements for each of these types of vehicles was conducted during the development of the integrated computer model.

The purpose of this work was to define the initial requirements for the specific vehicle classes that were to be considered as candidates for FCV propulsion power plants. Following development of the integrated computer simulation code, the FCV candidates were modeled and compared in more detail to investigate performance, fuel usage, range, etc, estimates over established driving cycles. Power train component packaging constraints and other factors, such as estimated ECE costs, were also included in the determination of the requirements of each candidate vehicle, allowing overall detailed comparisons to be conducted between each class of vehicle.

The entire analysis was designed to yield criteria that would result in a single vehicle type recommendation as the candidate for further FCV studies to be conducted under the Trade-off Analysis of Task 1.3. This section describes the initial assessment of the mission definition, i.e., selection of the vehicle types, the criteria used to establish the requirements for future FCVs, current ICE vehicle design and performance requirements, and, finally, projected FCV design and performance requirements.

VEHICLE TYPE SELECTION/CHARACTERISTICS

As described in detail in the Vehicle Specification Criteria section, future FCVs are projected to be required to equal or exceed the performance, operational convenience, and functionality of current products. Vehicle use and driving patterns are, therefore, consistent with those estimated from previous DOE studies for current vehicles. Realistic design and performance requirements for a proposed FCV are, consequently, based on review of available information on *current products*, their trends and projections, and expert opinion. Therefore, following the guidelines of the DOE, the vehicles chosen to be modeled by TASC and GMVS include three classes of passenger car (large, mid-size, and compact), two classes of multipurpose vans (mini-van and cargo van), and an urban transit bus.

Passenger Car

Spreadsheets (Appendix A) containing key vehicle performance parameters (e.g., weight, drag, rolling friction, acceleration) were created for three classes of passenger cars: large, mid-size, and compact. The key parameters for each class were averaged to develop a composite set of performance parameters for use in vehicle simulation studies. This resulted in a more representative set of vehicle power requirements than would be the case if a specific vehicle were chosen to be modeled.

The large passenger car class contains design and performance data for cars such as the Buick Roadmaster, Chevrolet Caprice, Lincoln Town Car, Cadillac Brougham, Cadillac Fleetwood, Cadillac DeVille, Olds 98, and Buick Park Avenue. The mid-size passenger car class considered design and performance data for cars such as the Buick Regal, Mercury Sable, Ford Taurus, and Honda Accord. Compact size passenger cars considered include the Chevrolet Cavalier, Ford Escort, Jeep/Eagle Talon, Honda Civic, Nissan Sentra, Mazda Protégé, and Toyota Tercel. From this set, a representative average performance requirement for each class of passenger car, including power train power output, was developed.

Van

A similar effort developed average performance requirements for two classes of a multipurpose vehicles. The data for this class of vehicle includes the GM APV, Mazda MPV, Ford Aerostar, Toyota Previa, and Dodge Caravan as mini-vans and the GMC Safari as a larger passenger/cargo van.

Urban Bus

The urban transit bus parameters from the DOE Fuel Cell/Battery Powered Bus Systems report were used for this data set. Thus, the urban bus was powered by a 50-kW PEM ECE operating at a converted voltage of 180 volts.

For the passenger cars and vans, component performance requirements were developed from analysis of several current vehicles in each class. These requirements, combined with ECE/battery characteristics described later, indicated that a continuously rated 60-kW ECE system yielded adequate performance; an 80-kW ECE system design is also considered a viable "high performance" option. For the urban bus, either a continuously rated 45-kW or 60-kW power ECE system would be required, depending on the specifics of the selected bus (50-kW was finally chosen). Sam Romano of Georgetown University provided GM with his Hybrid 30 simulation code for the urban bus; this code includes regenerative braking for bus-sized vehicles. If the urban bus is simulated in detail later in the Trade-off Analysis, it may be appropriate to integrate aspects of GMVS's vehicle simulation code and the Hybrid 30 code for urban bus application.

The analysis of performance data developed from the study of current vehicles, combined with projected ECE/battery characteristics, resulted in ECE System design specifications which dictate that a minimum of three levels of continuously operating power production devices, 45-kW, 60-kW, and 80-kW, will be required. Full power conditions can result in nearly a 150% intermittent peak power operating condition. Calculations to define the ECE system design parameters to produce these levels of continuously operating power were successfully performed by the JDC's ECE power source modeling code. Results of these calculations are used throughout this report and form the basis for the vehicle simulation runs described in later sections.

VEHICLE SPECIFICATION CRITERIA

Automotive industry leaders and academic researchers presented their forecasts regarding the future trends of automotive design, performance, and infrastructure at the 1992 Automotive News Congress in Detroit, MI. A compilation of their findings is presented in the University of Michigan Delphi VI Summary in which a trend toward reduced vehicle mass is predicted, but only if it is achieved through utilization of advanced materials, not by a reduction in vehicle size.

In light of the fact that industry spokesmen and academic researchers expect future vehicles to retain approximately the same size as today's vehicles, it is reasonable to assume that an FCV, circa 2000, will be reasonably well defined by the average vehicle characteristics (within each vehicle class) of today's vehicles.

Thus, as stated above, future FCVs are projected to equal or exceed customer expectations regarding the performance, operating convenience, and functionality of current products. Vehicle use and driving patterns are expected to remain consistent with those estimated from previous DOE studies for current vehicles. Realistic design and performance requirements for a proposed FCV are, consequently, based on a comprehensive review of available information on *current products* and their expected trends and projections.

The assumptions used in this report to establish values for FCV performance requirements differ from those chosen for the Jet Propulsion Laboratory (JPL) study. The JPL study assumed that the customer might be inclined to compromise performance expectations "in the interest of fuel economy and perceived reliability." Recent information from periodicals (for example, *Car & Driver*, January 1992), discussions at the 1992 Automotive News World Congress, and the opinions of automotive industry leaders indicate that individuals of the next decade are *less likely* to compromise vehicle performance issues.

Therefore, for the purpose of Task 1.2 and the requirement to recommend a single vehicle of choice for further trade-off analysis in Task 1.3, it was deemed appropriate to establish *current vehicle performance requirements* as objectives for the FCV. The single exception is the acceptance of a reduction in top speed compared to conventional ICE powered vehicles. This limitation is imposed because of the maximum rpm of electric motors. This compromise is considered acceptable since the top speed of the FCV would still well exceed maximum allowable legal speeds.

As a consequence, in this study the JPL assumption regarding potential customer acceptance of compromise is rejected. The FCV which *least compromises* current vehicle performance requirements heavily influences the recommendation procedure. This criteria applies to all of the vehicles considered in this report: passenger cars, vans, and urban transit buses. Particularly in the case of the urban bus, the performance of both the PEM and PAFC ECE power trains could be compared directly to that of the diesel powered test-bed bus over the identical driving cycle. Both the test-bed and PAFC buses have been analyzed in earlier DOE technical efforts.

CURRENT VEHICLE DESIGN/PERFORMANCE SPECIFICATIONS

Although FCVs will have different operational characteristics than current conventional ICE vehicles, it is desirable to minimize the impact of such differences on the customer. In order to evaluate the potential of the ECE in various FCV applications it is, therefore, necessary to determine the characteristics and specifications of the various vehicle types described in the Vehicle Selection section. Performance requirements for proposed FCVs will be established by specifying that they compare, where possible, to those of current conventional ICE vehicles. Thus, design and performance characteristics of proposed FCVs will be compared to those of current vehicle specifications, customer expectations, and analysis of trends expected for the next decade. Current vehicle specifications were determined and averaged for each vehicle classification under consideration and are presented in Table 3-I. This table is a condensation of the information compiled in Appendix A. Current vehicle design and performance specifications, as presented in Appendix A, were obtained from a variety of sources, including the following:

- American Automobile Manufacturers Association (AAMA) publications
- Manufacturers press release information
- Automotive periodicals
- Manufacturers' engineering departments
- JPL Advanced Vehicle Systems Assessment Study
- Library search of pertinent papers and trend analysis studies

Current vehicle information was collected in a common format for comparison and trend analysis. Except for data obtained in the AAMA publications, the design and performance specifications from the other sources were not published in a standard format. Data were estimated when validated values could not be obtained.

Table 3-I.
Design and performance specifications of sales weighted current average vehicles.

EPA classification	Large car	Mid-size car	Compact car	Mini-van	Urban bus
Design requirements					
Curb weight - kg/lb	1,650/3,631	1,358/2,988	1,082/2,380	1,624/3,574	8,181/18,000
Weight distribution - % front	59%	63%	62%	56%	34%
Wheelbase - cm/in.	287/113.1	271/106.5	252/99.4	288/113.5	445/175.0
Overall length - cm/in.	528/207.7	483/190.0	443/174.3	457/179.8	814/320.4
Overall width - cm/in.	191/75.2	178/70.0	169/66.6	184/72.5	229/90.0
Frontal area - m^2/ft^2	2.28/24.5	1.97/21.2	1.89/20.3	2.76/29.7	6.41/69.0
Drag coefficient - C_D	0.34	0.35	0.35	0.35	0.60
Number of passengers	6	6	5	7	25
EPA total volume - m^3/ft^3	3.68/129.8	3.14/110.8	2.85/100.7	4.24/149.7	29.1/1,027
EPA trunk volume - m^3/ft^3	0.573/20.2	0.465/16.4	0.396/14.0	0.609/21.5	NA
EPA passenger vol. - m^3/ft^3	3.10/109.6	2.67/94.3	2.46/86.7	3.57/126.1	29.1/1,027
Performance requirements					
0 to 96.6 km/hr (60 mph) sec	9.5	9.1	9.3	11.3	NA
Top speed - km/hr/mph	174/108	183/114	179/111	169/105	97/60
Short-term maximum grade negotiable	30%	30%	30%	30%	16%
Long-term maximum grade negotiable @ 96.6 km/hr	6%	6%	6%	6%	NA
Range - FHDS (km/mi)	809/503	742/461	704/438	731/454	240/150
Range - FUDS (km/mi)	522/324	527/327	554/344	585/363	NA
Start up & drive away (sec)	<20	<20	<20	<20	<1980
Long-term storage (days) for ambient start @ 70°F/21°C	35	35	35	35	35
Fuel Economy					
EPA highway - km/L /mpg	10.92/25.7	12.21/28.7	13.35/31.4	9.36/22.0	NA
EPA urban - km/L /mpg	7.28/17.1	8.87/20.9	10.46/24.6	7.28/17.1	1.06/2.5

Sources of Current Vehicle Specifications

A description of each of the sources of current vehicle specifications and the data contained within it is presented below.

American Automobile Manufacturers Association

AAMA requests that each manufacturer complete a standard form, verify it, and submit it for publication within a designated period following production release of each new vehicle. This form includes a list of all options and combinations available within the product line. Once the AAMA document is submitted, the matter of public distribution is left to the discretion of the manufacturer. AAMA also provides a list of representatives for each U.S. manufacturer. A related agency, the Association of International Automobile Manufacturers (AIAM) also collects data and provides a list of representatives for international manufacturers in the United States. AAMA, AIAM, and manufacturers' representatives were contacted to obtain current vehicle specification data submitted to the associations. In many cases the manufacturers' representatives were able to supply additional supplementary data.

Manufacturers' Press Release Information

Manufacturers' press release information was used to supplement the AAMA and AIAM data. Press release information is not published in any common or standardized manner, therefore consistent design and performance specifications were not readily available from this source. Whenever possible, the Manufacturers' press release information was incorporated into the data format developed for the purpose of this study.

Automotive Periodicals

Numerous automotive monthly publications discuss and/or analyze the design and performance of current production vehicles. A few of these actually have or employ testing facilities to measure the static and dynamic performance of various vehicles. Data from these publications were helpful in estimating the design and performance specifications when the manufacturer's data were insufficient. The publications often presented comparisons between current and previous model year vehicles. These publications also include projections relating to vehicle trends and customer expectations. The publications surveyed during this study included:

- *Automotive News*
- *Car & Driver*
- *Motor Trend*
- *Road and Track*
- *Automobile Magazine*

In general, these periodicals tended to evaluate sporty and high image vehicles while providing minimal comparative analysis on economy and base level product lines.

Manufacturers' Engineering Departments

When insufficient AAMA or manufacturers press release information was received, vehicle manufacturers' engineering departments were directly contacted. In many instances the engineering departments were able to provide verbal clarification of various items or provide missing data.

JPL Advanced Vehicle Systems Assessment Study

An Advanced Vehicle Systems Assessment Study was conducted several years ago by the JPL. The purpose of this study was to assess the potential capabilities of nonpetroleum powered passenger vehicles to compete with conventional vehicles in the 1990s time frame. The five volume study was conducted for the U.S. Department of Energy (DOE/CS-54209-22) and was published in March, 1985. Where applicable, the methodology and resource information contained within the JPL study were utilized to support this effort; information considered especially useful is included in Section III, Systems Assessment.

Library Search

Library searches were also necessary to obtain current vehicle specifications, reports, and trend projections. Where applicable, forecasts and analysis studies for the U.S. automotive industry were incorporated in the data base. These forecasts included such studies as the University of Michigan Automotive Delphi Surveys.

Compilation of Current Vehicle Specification Data

Current vehicle design and performance specifications obtained through all of the above sources were collected and compiled into the standardized spreadsheet format presented in Appendix A. This spreadsheet contains published design and performance specifications and includes calculations based on those specifications. The objective of the spreadsheet is to record current vehicle parameters that would be pertinent to the scope of this project. The recorded information was then used for comparison purposes within each vehicle classification and provided projections for future FCV specifications. The most complete vehicle information available was used in the spreadsheet. Vehicle information was updated as more recent or more reliable information became available.

In line with the scope of the project, information included EPA data for large, mid-size, and compact passenger cars. Vehicles such as the Chevrolet Lumina-APV and Plymouth Voyager are classified by the EPA as two-wheel drive special purpose vehicles, and are referred to in the study as mini-vans. Detailed bus specifications were defined in the earlier DOE Fuel Cell/Battery Powered Bus Systems report and, thus, were not included in the spreadsheet. Appendix A also presents the spreadsheet data in a graphical format which is useful for comparison and trend studies. The majority of the specifications are published, with some being estimated as required. Estimated information is italicized in the spreadsheet to distinguish it from validated data. The remainder of the spreadsheet parameters are calculated. Each of the parameters contained in the spreadsheet is described below.

Vehicle Identification

This information identifies the exact year, manufacturer, model, and EPA class for each vehicle specified. A vehicle number is included for identification purposes only.

Design Specifications

Eighteen published specifications about the vehicle are listed. Many of these were obtained from AAMA releases. Shadow area is defined as the vehicle length multiplied by the vehicle width and approximates the vehicle footprint area. Although not used in this report, other studies have defined it to be useful.

Component Mass Estimates

The exact vehicle component masses were difficult to obtain, so a series of linear equations was developed to estimate the major contributors to the current vehicle power train mass including engine, transmission, and fluids. These regressions were developed based on the vehicle power train masses which could be obtained from the AAMA. Other engine and transmission data which are not specific to automobiles also contributed to these correlations. The resulting mass estimate equations are listed below:

• Dressed Engine	56.70 kg/L of engine displacement
• Transmission and Torque Converter	17.24 kg/L of engine displacement
• Fuel Tank (dry)	0.16 kg/L of fuel tank capacity
• Fluids	specific gravity of fluid times fluid volume
• Power train	total of above 4 masses

EPA

The EPA volume index and mileage were obtained from published data. Passenger volume was calculated as the difference between EPA total volume index and trunk volume.

Performance

Vehicle straight line performance was obtained from the EPA, manufacturers, and third party published road test data. The complete content and option level of the tested vehicles is not known, however, it may be assumed that the values fall within an acceptable variance for each specified vehicle. For purposes of this study, several performance criteria are necessary to compare vehicles. In several instances the desired vehicle performance specifications were either not included or those available were different from the selected criteria. In these instances, estimates were recorded in the spreadsheet and identified by italics.

Average Accelerations

Vehicle maximum straight line acceleration depends on many factors including engine power, transmission gearing, weight distribution, tires, etc. These characteristics also influence the details of the velocity-time history of various vehicles. This level of detail falls outside the scope of this recommendation study. Accordingly, vehicles were considered to have equal performance if they had equal 0 to 96.6 km/hr acceleration time. These calculations were primarily intended to be used in comparison and trend analysis studies and not as estimates of manufacturer or third party testing results.

Coast-Down Power

Level road coast-down power (to maintain vehicle speed) was included. In many instances, manufacturers' or testing facilities' published coast-down data are presented for different vehicle speeds desired rather than the desired standaridized velocity. Test results were, therefore, not available for many vehicles or lacked sufficient information to confirm an exact match with the intended vehicle specification. Coast-down power was estimated only where sufficient comparisons to similar vehicles or expert opinion could be considered reliable.

Range Estimated

Range was calculated as the EPA highway fuel economy multiplied by the fuel tank capacity. This provided a common method to estimate and compare results. The calculation was not intended to replace manufacturer or third party testing results.

FCV Conversion

The FCV conversion parameters were included only to provide estimates of a FCV version of the vehicle specification. This portion of the spreadsheet serves as a method to quickly estimate the total mass of an FCV. The mass of the FCV minus power train (chassis and body only) was estimated by subtracting the conventional ICE power train mass estimate from the vehicle curb mass. The FCV curb mass is estimated in a later section by adding the electric drive system, battery pack, and ECE power system mass estimates to the chassis and body only mass estimate.

Sales Data

Figures in this row represent the unit sales of each of the individual vehicles during model year 1991 (Source: *Automotive News).*

Current Vehicle Design and Performance Comparisons

The characteristics of current vehicles were compared to assist in the definition of the FCVs. Comparisons were made within EPA vehicle classifications to identify similarities, extremes, and trends. The spreadsheet was the basis for the current vehicle comparison analysis. Comparisons were made in four distinct EPA classifications:

- Large Car
- Mid-Size Car
- Compact Car
- Mini-Van

Vehicle comparisons within EPA classifications included:

- EPA total volume index
- Shadow area and wheel base
- Vehicle curb mass
- 0 to 60 mph (0 to 96.6 km/hr) time
- Vehicle range at highway speed
- Vehicles sold annually (1991)
- Retail price (1992)

Specifications for an urban bus were not included in the spreadsheet since the approach was to match the specifications of the bus outlined in the earlier DOE Fuel Cell/Battery Powered Bus Systems report.

Vehicle comparisons within EPA classifications are also presented graphically within Appendix A. Sales weighted averages of the comparison values were calculated based on the number of vehicles sold according to 1991 U.S. sales data (*Automotive News, 1992 Market Data Book*). Sales weighted current average design and performance specifications for each EPA classification (for which data were attained and presented in Appendix A) are presented in Table 3-I.

In light of the fact that industry spokesmen and academic researchers expect future vehicles to approximately retain the same size as today's vehicles, it is reasonable to assume that projected FCVs will be reasonably well defined by the average vehicle characteristics presented in Table 3-I. Furthermore, four representative GM vehicles were selected because their characteristics were close to the corresponding average specifications presented in Table 3-I. Using specific vehicles was also advantageous because additional detail would be available should it be required in the Trade-off Analysis Study of Task 1.3. The four vehicles are:

- Large Car Vehicle — 1992 Cadillac Fleetwood
- Mid-Size Car Vehicle — 1992 Buick Regal
- Compact Car Vehicle — 1992 Chevrolet 4DR Cavalier
- Mini-Van Vehicle — 1992 Chevrolet APV Lumina

Therefore, the design requirements necessary for the vehicle evaluation and recommendation in Task 1.2 are taken to be the specifications of the above current vehicles. The Trade-off Analysis Report, to be written from work performed under Task 1.3, may include additional requirements and specifications.

VEHICLE DESIGN AND PERFORMANCE REQUIREMENTS

The objective of this portion of the study is to establish realistic design and performance requirements for FCVs. FCV requirements were established after carefully reviewing the profile and specifications of current vehicles. The data in the vehicle spreadsheet (Appendix A) were used primarily to assist in vehicle design and performance requirements for FCV passenger cars and vans.

Vehicle Design Requirements

FCV design requirements were established after a careful review of the comparisons of current vehicle profile and specifications (fromAppendix A), Delphi VI Summary trend forecasts, and a review of vehicle specifications in *Automotive News and Markets* data book issues. As stated, the sales weighted average values of the design specifications of various car classifications, presented in Table 3-I, are taken to be representative of FCV designs for the next several years. Downsizing of future FCVs is not considered to be a viable option.

Vehicle Performance Requirements

FCV performance parameters were established after careful review of: current vehicle performance specifications, future performance projections, the JPL Advanced Vehicle Assessment Study, and independent projections made by GMVS.

The parameters established for each of the vehicle classifications are, for the most part, the current performance capabilities of the sales weighted average vehicle in the appropriate EPA classification, as presented in Table 3-I.

The initial assessment of the mission definition, power, and power train requirements for each of the vehicles under consideration was conducted during the development of the integrated computer model. As the start-up time of the ECE is projected to be longer than that of its ICE counterpart (perhaps as long as two minutes total start-up time), two different types of FCVs were considered. A "maximum performance" FCV can achieve the 0 to 96.6 km/hr acceleration time of a comparison conventional ICE vehicle when the ECE is in a start-up mode. A "similar performance" FCV, on the other hand, is required to meet only the acceleration requirements of the FUDS while the ECE is in start-up mode. The preliminary battery size was determined by requiring the battery power to be sufficient to drive the vehicle during ECE cold start-up. Various scenarios of projected ECE start-up times and transient response were utilized so that an envelope of projected ECE/battery power ratios was considered; therefore, the vehicles differ in the amount of batteries required.

The initial ECE power requirement was established by gradeability requirements. FCV gradeability has both short- and long-term requirements. Short-term gradeability requirements match the maximum hill climbing ability of a conventional ICE vehicle. It is assumed that the vehicle starts from rest and travels at slow speeds a maximum distance of 100 meters. Long-term gradeability requirements were established by sizing the PEM ECE such that it could propel the vehicle up a 6% grade at 96.6 km/hr (60 mph). This grade and speed requirement results from design standards for interstate systems determined by the American Association of State Highway and Transportation Officials.

Start-up and drive away requirements used to initially establish the battery energy carried on board the vehicle may appear excessive; however, these requirements were established by considering procedures from vehicle manufacturers and reputable research councils. Vehicle manufacturers have comparatively severe start-up and drive away specifications. For example, start-up and drive away times are specified to be as low as 1 second when ambient temperature is greater than 0°C, and is 5 seconds when ambient temperature is below 0°C. In contrast, the Coordinating Research Council (CRC) publishes less severe start-up and drive away procedures for automotive applications. The CRC studies relationships between automotive engines, fuels and lubricants, and atmospheric reactions of automotive emissions. Their testing procedures are used extensively by petroleum industries in evaluating fuels and lubricants. The standard CRC test requires a 20 second start-up and drive away time for current ICE vehicles. It was decided, however, that the FCV should meet the shorter requirement to be consistent with customer expectations and current products.

Thus, these initial calculations predicted preliminary ECE/battery power train subsystem and component sizes based on performance requirements over a prescribed driving cycle. The validity of the computations was then determined through simulation of each of the three vehicle types while considering technical constraints set by the ECE system vehicle packaging requirements. These vehicle simulation analyses recalculated and/or verified preliminary recommended combinations of ECE and battery power based on optimization of performance, range, energy usage, and various other factors. These FCV performance criteria are described in more detail in the Vehicle Evaluation Criteria/Procedure portion of Section IV. As might be expected, the maximum performance vehicle also requires a larger ECE to satisfy the gradeability requirement due to the additional weight of the larger battery pack.

Vehicle Use Patterns/Driving Schedules

The differences between a conventional ICE powered vehicle and an FCV present a challenge in comparing vehicle usage. While the performance of the conventional ICE vehicle is relatively unaffected by long-term storage, the FCV performance may be affected because of battery self-discharge and the longer start-up period for the ECE; however, these factors are not relevant to the vehicle recommendation portion of Task 1.2. As defined in this report, a future FCV will have design and performance characteristics comparable to those of current conventional vehicles; therefore, as all future FCVs will experience similar battery-related self-discharge and start-up characteristics, the vehicle recommendation criteria will be made based on performance, packaging constraints, energy consumption, and range.

FCV computer simulations were used to check the performance, energy consumption, range, etc, of the various vehicles under consideration. This required the selection of a prescribed driving cycle to determine the validity of (or necessity to recompute) the preliminary recommended combination of ECE and battery power. Iterating procedures are required as final packaging constraints and vehicle weights are determined prior to the development of the integrated simulation model. Considering the FCV to have similar performance to that of current vehicles, the prescribed driving cycle was specified by utilizing the FUDS and FHDS for the automobile and van. These driving schedules are published by the EPA and details of both are contained in Appendix B.

The DOT/UMTA Transit Coach duty cycle was established in earlier DOE work to evaluate a PAFC ECE/battery hybrid bus serving Georgetown University.

IV. VEHICLE SIMULATION AND EVALUATION

The objectives of determining and defining conceptual FCV design and performance requirements based on current vehicle specifications are to establish a procedure by which rational analysis of the vehicle sets can be accomplished and to present a vehicle recommendation based on that analysis to DOE's Technical Manager. To do this, a conceptual FCV design must consider a variety of power train configurations, components, and component sizing methods.

VEHICLE POWER TRAIN CONFIGURATION

A series connected electric power train configuration was chosen for the conceptual vehicle design (see Figure 4-1). Front wheel drive was assumed, which is consistent with current trends and projections. This also provides the most economical use of space when dealing with space frame and unibody systems. The power train configuration and components of the urban transit bus were identical to those of earlier DOE studies.

Energy flow in the FCV is presented in Figure 4-1. Liquid fuel (e.g. methanol) is converted to dc electricity by the ECE. This energy is directed into the batteries or to the inverter depending on instantaneous demand. The inverter controls power flow to the electric motor(s) which propels the vehicle. This configuration allows the vehicle to be powered by the battery alone, the ECE alone, or a combination of both. The control strategy employed allows for intelligent load sharing between the ECE and the battery depending on the driving requirements and state of charge (SOC) of the batteries. Energy required for the accessories is obtained from the same source delivering power to the inverter.

Regenerative braking energy is produced while decelerating the vehicle by back driving the electric drive motor(s). This technique is utilized first during braking situations in lieu of friction braking. Conventional brakes are phased in when the batteries cannot accept deceleration energy at the required rate. Regenerative braking can have a significant effect on energy conservation and thus overall fuel economy.

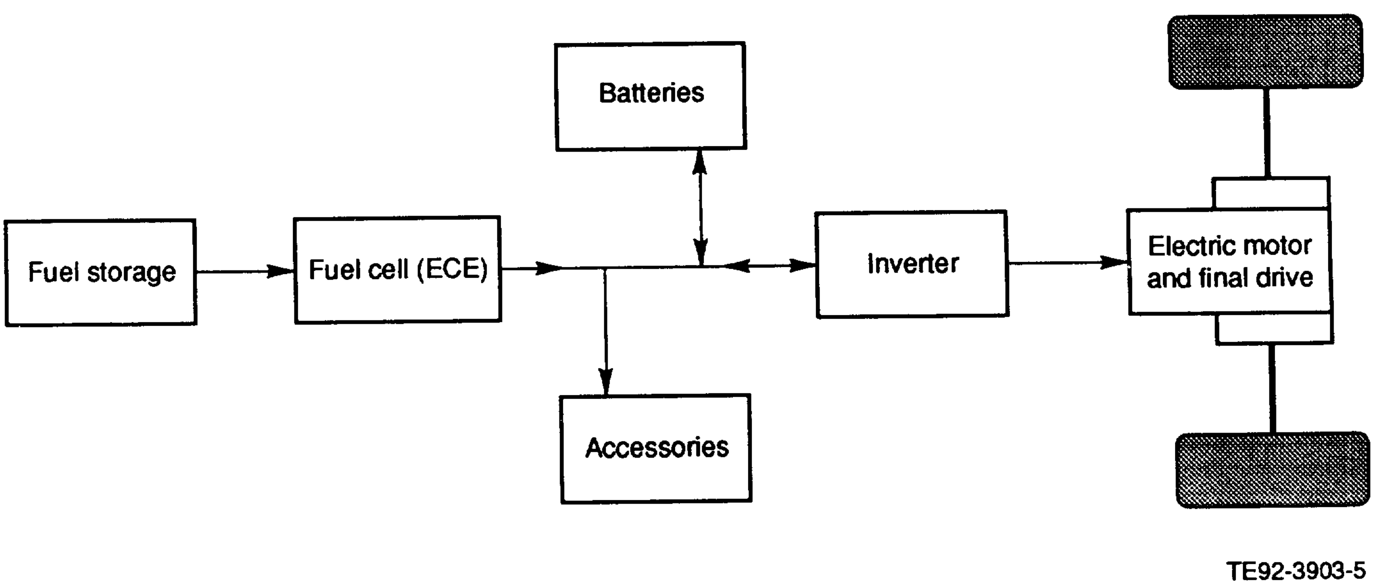


Figure 4-1. Power train configuration.

All of the electrical drivetrain components, with the exception of the ECE, chosen for this conceptual FCV design were based on GM's Impact electric vehicle. Impact represents the leading edge for electric drive components that might be delivered in the near future. The ECE and the other component technologies are described below.

The PEM Electrochemical Engine

Among the candidate power plants for the engine/charging system, the indirect methanol PEM ECE is potentially the most efficient, as the device is unrestricted by heat engine (Carnot cycle) limitations. The ECE is a power producing system formed by the integration of four components:

- a fuel processor that converts liquid methanol to a hydrogen-rich gas
- a PEM fuel cell stack, driven by the hydrogen-rich gas through electrochemical conversion with air as the oxidant, that generates dc electrical power
- auxiliaries, including a turbocompressor that pumps air to increase pressure and also incorporates an expander to utilize residual heated exhaust air to provide part of the compression energy
- controls for the entire system that provide thermal and water management systems and respond to power-management requests from the vehicle controller.

Similar to an ICE, the ECE power system consumes liquid fuel (methanol stored in the fuel tank) but converts the fuel energy directly to electrical energy. The ECE is expected to feature sharply lowered emissions, high First-Law efficiency, and convenient refueling.

The ECE design must be carefully configured to attain desired efficiency goals, i.e., thermal integration within the device is an important consideration. In general, the energy for the endothermic (heat requiring) fuel processing component is provided by burning the exothermic (heat releasing) excess fuel cell stack anode vent gases. A combustor assembly, that can combust either methanol (for start-up operation) or the excess hydrogen exiting from the anode compartment of the fuel cell stack, is utilized to provide the heat energy required for fuel processing. Detailed modeling of the ECE system indicates that overall system efficiency improves as excess hydrogen, rather than methanol, is utilized within the combustor. System efficiency can be further increased if the heat that is produced within the fuel cell stack, and subsequently transferred to the stack cooling loop, is ultimately utilized for partial or complete methanol vaporization. The burner exhaust, after heating the fuel processing component, still contains significant energy. System efficiency can be further increased if this remaining energy is used to raise the enthalpy of the excess cathode air entering the expander portion of the turboexpander, thereby providing a portion of the energy input requirement of the compressor.

A preliminary system schematic is presented in Figure 4-2. The various components of the system are identified by a code number (e.g., 3 for the reformer). The main integrated components are:

- the fuel processor in the upper-left of the figure (the burner is part of the fuel processing component)
- the compressor-expander component at the bottom center
- the fuel cell stack in the upper-right
- the heat rejection and water management system at the bottom-right.

The control system is not specifically indicated on this schematic. Heat flow occurs through the nine heat exchangers that connect the components described above. Each of these major components is described below.

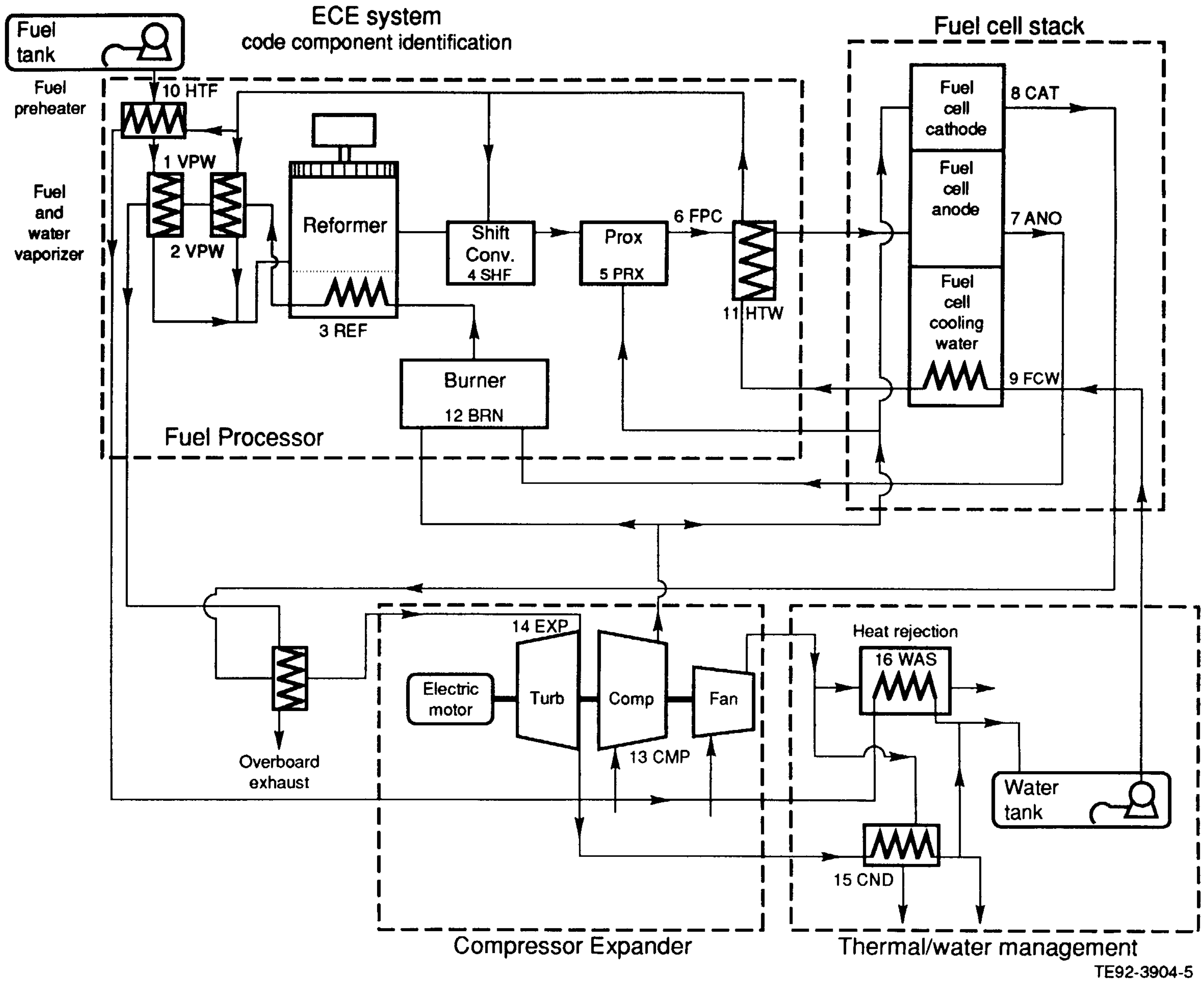


Figure 4-2. ECE system component identification.

Fuel Processor

Methanol is pumped into the system, preheated by the stack cooling loop (10) and vaporized (if required) by the burner exhaust (1). Part of the cooling loop water, which is already preheated in the stack and the preferential oxidation unit (PROX) components, is separated from the main coolant loop and is vaporized into steam by the burner exhaust (2). A controlled mixture of steam and methanol (usually in a steam-to-methanol molar ratio of 1.3) is then injected into the reformer (3), which is a heterogeneous recirculating gas catalytic converter. Within this device, methanol and steam are processed into hydrogen (H_2), carbon dioxide (CO_2), excess water vapor, and trace quantities of carbon monoxide (CO) and methanol (CH_3OH). The resulting fuel mixture exiting the reformer is cooled and additional water is added to the gas stream in the shift converter (4). Within the shift converter, much of the residual, nonreacted methanol is converted to H_2, and the concentration of CO, a severe fuel cell stack poison that can cause temporary system degradation, is reduced by a factor of three or more. Finally, the H_2-rich stream enters the PROX (5). In this unit, a small volume of air is fed into the product stream, and oxygen (O_2) within the air reacts with any remaining residual methanol and CO to clean the stream of those contaminants. The fuel processor thus produces a stream of H_2, CO_2, and some steam with acceptably low levels of CO, methanol, and other contaminants. Finally, the gas stream is cooled to approximately 100°C (11), humidified to saturation conditions, and flows through the anode side of the fuel cell stack.

Compressor-Expander

Excess ambient air (stoichiometry ≈2.0) is compressed (13) to about 3 atmospheres absolute and fed to the air/cathode side of the fuel cell stack. Compression work is provided both from an electric motor and the expansion (14) of the burner exhaust heated excess cathode air stream. Under operational conditions, significant quantities of the compression work can be supplied by the expander. The exhaust stream (8) from the cathode is saturated and contains entrained liquid water. Even though this stream is heated by the burner exhaust, expansion through the expander results in two-phase flow. Because of this phenomenon, scroll expanders or other design types that accept such two-phase flow conditions are required. Water-cooled scroll compressors, because of their high efficiency over wide variations in flow rate and part power operation, are also under consideration as the primary device composing the air compression system. The expander/electric motor also drives a low pressure fan to provide cooling air to remove heat from the cooling water. This fan/heat exchanger system acts essentially as does a radiator in current ICE vehicles.

Fuel Cell Stack

The fuel cell stack accepts the air and the H_2-rich stream on appropriate sides of a platinum alloy coated proton-exchange membrane. Electricity is produced as the primary product and supplied to the power bus in the vehicle. During the electrochemical electricity production, the conversion is not 100% efficient. Some of the chemical energy is degraded into heat that is removed by internal stack cooling. In most contemporary PEM stack designs, liquid water enters the stack for two purposes:

- some flows into gas stream humidifiers and is used to humidify the two reactant streams; humidification is necessary for optimum fuel cell stack performance
- the remainder (9) is used to cool the stack

Cooling is accomplished by cross flow through the bipolar plates at a rate necessary to maintain the desired operational temperature. The fuel cell stack accepts the stream of H_2 and CO_2 (with some steam) as the fuel input. Not all of the H_2 is effectively utilized; as the H_2 is depleted, the mole fraction of CO_2 increases such that additional fuel cell reactions are not practical. That stream then exhausts to the burner (12) where the residual H_2 is burned.

Heat Rejection and Water Management System

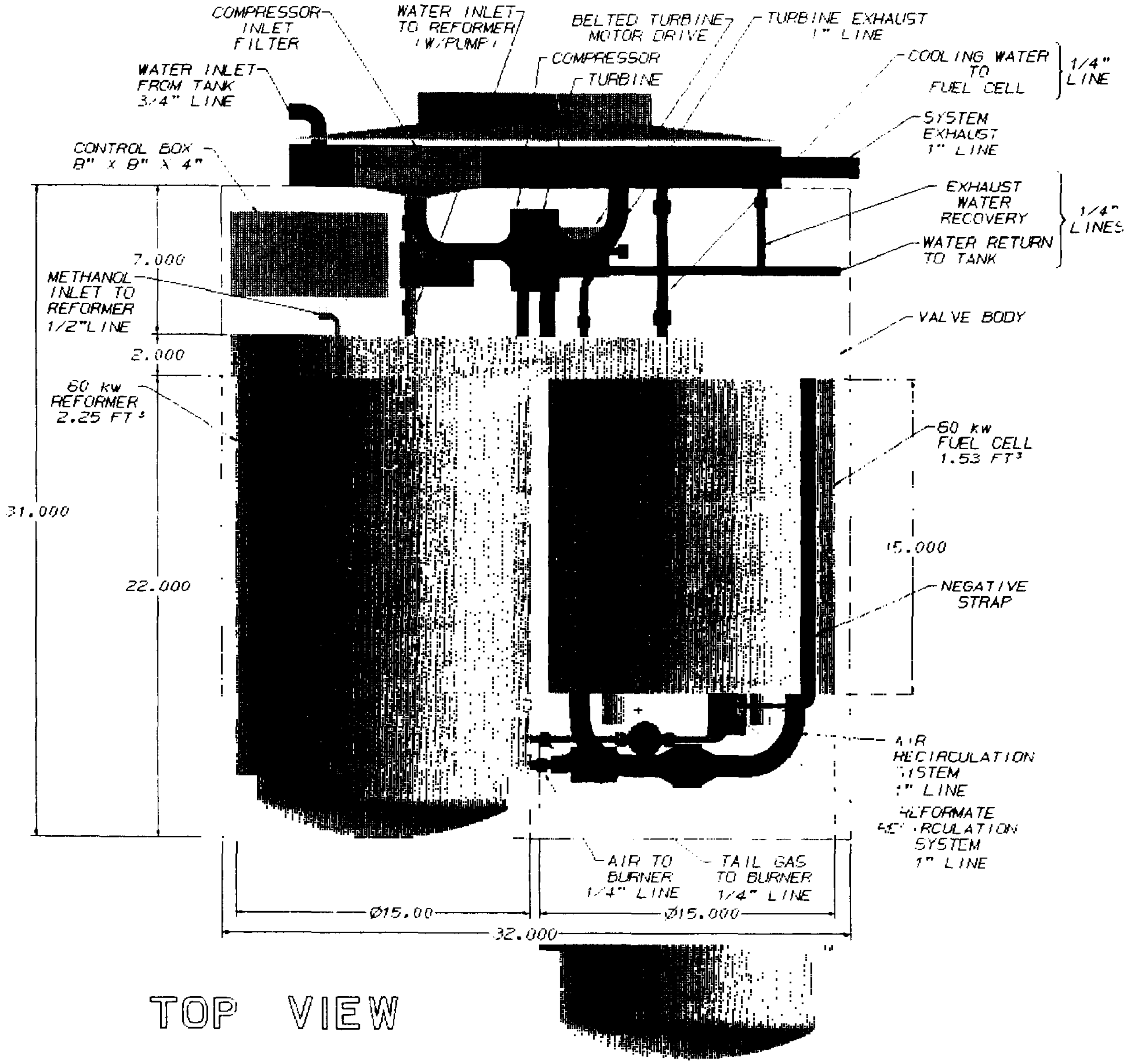
The majority of product water is removed from the air exhaust in a condenser prior to exiting the system. This air exhaust is a two-phase mixture (with considerable entrained water) which is heated by the combustor exhaust within a heat exchanger and then flows to the expander. The expander exhaust feeds to an air-cooled condenser (15) where the majority of the water is recovered. This high-purity water stream serves as cooling/humidification water for the fuel cell stack and feed water for the fuel processor. Water that is not condensed is discharged. System heat is rejected in the radiator at nearly the operating temperature of the fuel cell stack. Water circulation, driven by the water pump shown in the bottom right-hand side of the schematic, transfers heat from the stack and PROX into a larger exchanger, which is similar to a current ICE vehicle radiator. Most of the system heat rejection occurs in this air-liquid device. While not described, a sophisticated control system is required to coordinate all of the subsystems of the ECE into a functioning device capable of delivering power on demand.

ECE Subsystem Sizing

This ECE system produces electric power at high efficiency (>50% under steady-state conditions) and has the potential to meet the mass and volumetric power densities required for transportation applications. Although the fuel cell stack rapidly responds to load transients, other parts of the ECE system (the fuel processor) presently limit idle-to-full power transient response to 7-10 seconds. Start-up from cold conditions may require two or more minutes. This is one of the reasons that the series-electric power train, including batteries, was chosen. Batteries can provide the initial power during ECE warm-up and are useful in smoothing both up and down transients. Even if the ECE transient-response capability is improved, batteries are important to accept power generated during regenerative braking, improving fuel efficiency in stop-and-go driving.

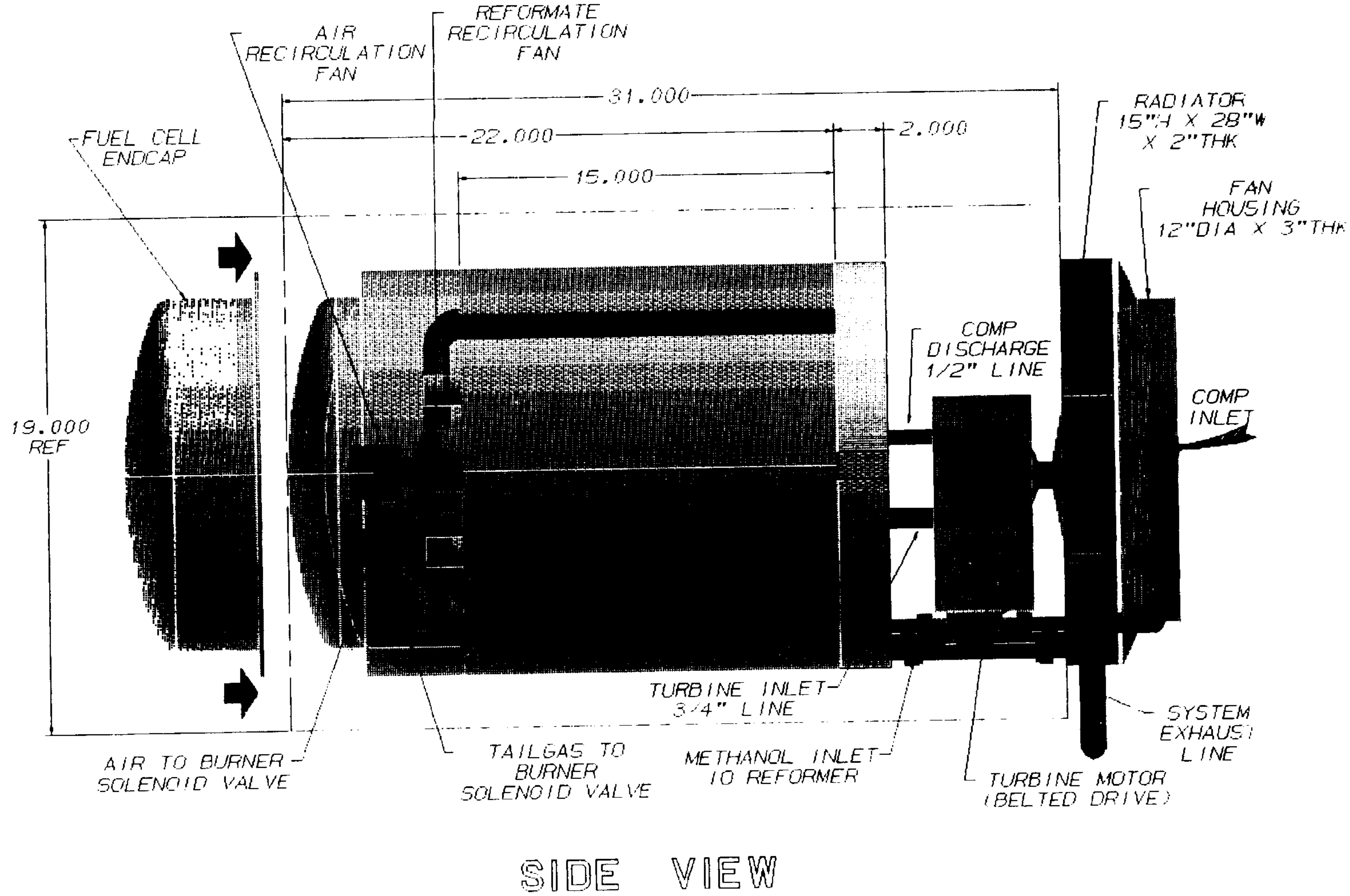
Optimized configurations of an ECE system, i.e. the fuel processor, fuel cell stack power generator, auxiliaries, thermal, water, and control management should be nearly comparable on a mass and volume basis with future ICEs designed to meet California ULEV or near-zero emission standards. If this is not the case, then future FCVs will not possess the full potential to extend the overall range and load carrying capacity of all electric vehicles.

Important aspects of this study of FCV performance, then, are the mass and volume of the ECE power source component. Recognizing that an ECE system design can only be estimated, as no automotive systems presently exist, all subsystem design projections were based on a full-scale preliminary design. The GM/LANL JDC team developed an initial preliminary design for an ECE system power plant capable of 40-kW continuous operation (60-kW peak ECE system power) based on the schematic layout previously described. This preliminary design, depicted in Figures 4-3 and 4-4, utilizes advanced fuel processing (monolithic catalyst supports, annular burners, light weight automotive heat exchangers/vaporizers, and advanced automotive methanol/deionized water pumps) concepts presently being developed by AC Rochester, Harrison Radiator, and the Allison Divisions of GM. Advanced fuel cell stack concepts such as thin, coated metal bipolar plates, membrane and electrode assemblies with low Pt alloy loading, anode and cathode pumped humidification/recirculation systems, unique gaskets, seals, and containment vessels under development by Allison , LANL, Dow Chemical Company, and the NAO R&D Physical Chemistry Department were also considered in the design. Advanced air, thermal, and water management (scroll compressor/expander, deionized water pumps, condensers, fuel and water tanks, and radiators) concepts under development by AC Rochester and Harrison Radiator, and an advanced control system (being developed by Allison and GMVS) based on GM's electric vehicle experience) were all considered important components of the preliminary design.



TE92-3905
VS91-2072

Figure 4-3. Top view of 40-kW (maximum continuous output) ECE mock-up.



TE92-3906
VS91-2074

Figure 4-4. Side view of 40-kW (maximum continuous output) ECE mock-up.

In an effort to gain additional understanding of the system design requirements, the full-scale mock-up was fabricated. This mock-up easily fits within the under hood dimensional constraints of a GM APV. Subsequently, the vehicle requirements discussed earlier in this report for the set of vehicles in this study indicated that power plants capable of producing continuous maximum output greater than 40-kW are required in the simulations/evaluations. Based on the design and fabrication of the mock-up, and analytical analysis of the component subsystems comprising the mock-up, the JDC was able to project ECE system mass and volume as a function of ECE system power output. These projections were based on ECE systems that the JDC believes, based on experience to date, can be designed and developed within the next five years. The ECE system mass and volume projections, as a function of power output, are presented as the top curves of Figures 4-5 and 4-6.

Results of the projections indicate, in general, a total ECE system mass on a continuously operating basis, of approximately 4 kg/kW (2.8 kg/kW on a peak power basis), about one and a half times the value now common in ICE design, but about five times lighter than previous ECE designs. The system mass is approximately equally divided between the fuel cell stack, the fuel processing stream, and the components necessary for thermal, water, air, and control management.

ECE System Costs

The optimized ECE system must also be comparable on an initial purchase cost basis with future ICEs designed to meet California ULEV/ZEV emission standards. Life cycle costs or total cost of ownership, including such elements as fuel, maintenance, insurance, licensing, etc, are also important to the customer and will be addressed in the Trade-Off Analysis Report. This logic also applies to the other power train components described below. Recognizing these are important issues, this report attempts to estimate ECE system costs in Appendix C. However, in the context of the vehicle recommendation criteria, it should be recognized that each vehicle has a similar ECE system and electric power train drive. Therefore, in a comparison among candidate vehicles ECE system and electric power train costs are not major criteria.

Electric Power Train System

The electric power train system consists of a battery pack, and an electric drive system. These components reflect characteristics of GM's Impact vehicle.

Battery

The battery is assumed to be a state-of-the-art lead-acid battery. It is used primarily for initial start-up and surge power thus requiring high power density. Lead-acid battery technology was chosen for reasons of cost, robustness, industry experience, and availability for transportation systems. The power density of this lead-acid battery is higher than many other battery technologies, a result of having been optimized for vehicular application. Future high power density batteries, however, could improve the vehicle performance estimated in this report. The battery nominal specifications are:

- type — sealed lead-acid, gas recombinant
- voltage — 10V per module
- capacity — 42.5 A-hr
- mass — 12.4 kg (27.2 lb) per module
- volume — 5752 cm^3 (351 in^3) per module
- power density — 250 W/kg
- energy density — 34 W-hr/kg

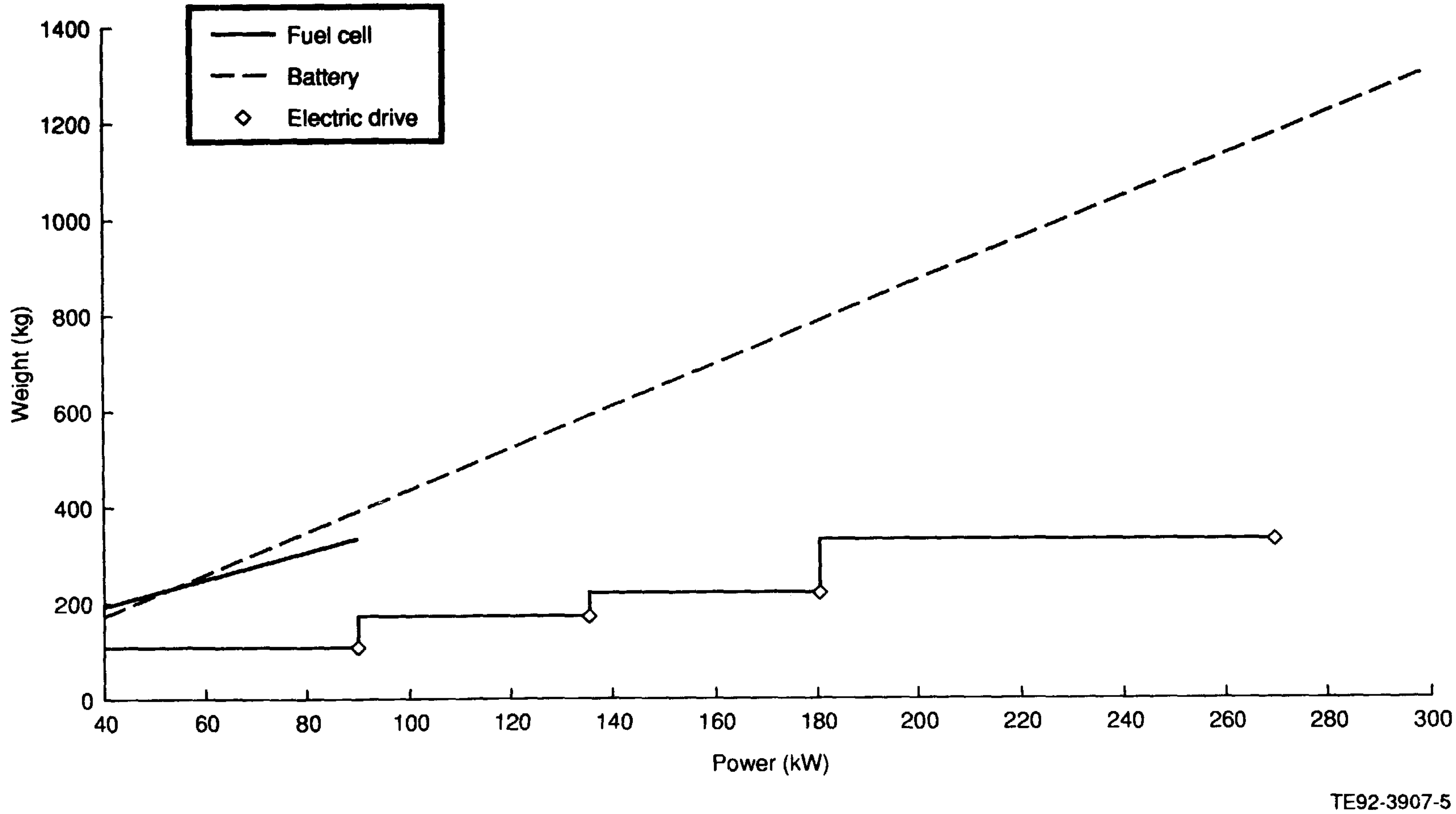


Figure 4-5. Component mass as a function of power output.

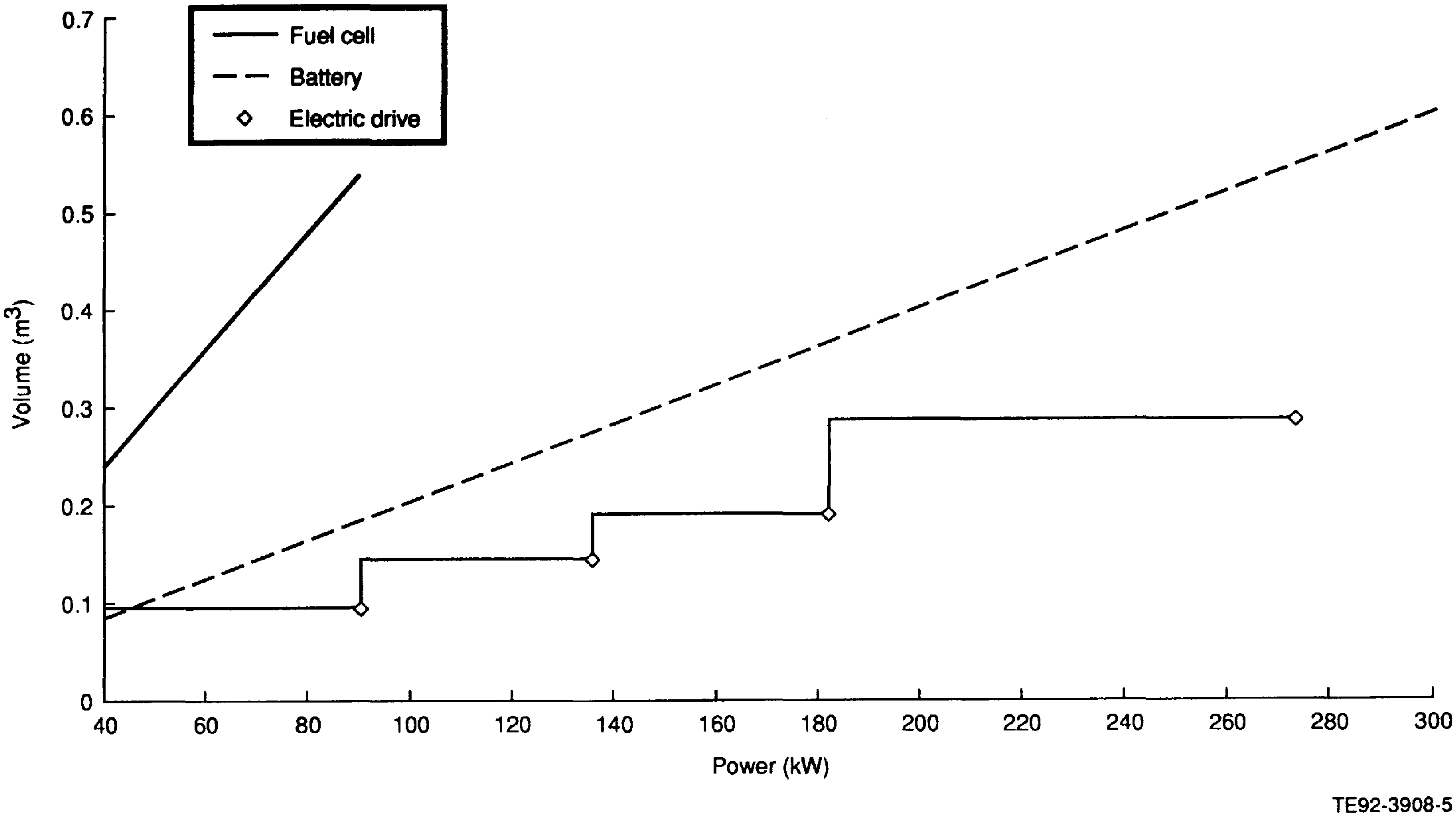


Figure 4-6. Component volume as a function of power output.

Electric Drive System The electric drive system consists of the inverter, the ac induction motor, the final drive/gear reduction, and the control system necessary to interface with the ECE and batteries. The nominal characteristics listed below represent a 90-kW state of the art system.

maximum inverter voltge	400V ac
maximum inverter current	318A
inverter frequency range	0-500Hz
ac induction motor efficiency	90-95%
ac induction motor max speed	12,000 rpm
ac induction motor max power	90-kW @ 6600 motor shaft rpm
ac induction motor max torque	94 lb-ft @ 6000 motor shaft rpm
electric drive system mass	110 kg (243 lb)
electric drive system volume	0.192 m^3 (6.7 ft^3)

Urban bus comparisons are based on the dc motor specified in the DOE Fuel Cell/Battery Powered Bus Systems report. The component mass and volumes of the battery pack, ECE, and electric drive system as a function of power output are also presented in Figures 4-5 and 4-6. This data is used later in this section to calculate component sizes and vehicle packaging constraints. It is assumed for the purposes of this report that electric drivetrain units, with the above nominal characteristics, would be available in 45-kW, 90-kW, 135-kW, 180-kW, etc.

VEHICLE SIMULATION METHODOLOGY

Future FCVs are assumed within this report to be required to equal or exceed the performance, operational convenience, and functionality of current products. Design and performance requirements for a proposed FCV were, therefore, based on a review of available information on *current products*, their trends and projection, and expert opinion. It was assumed that such a FCV, even circa 2000, is reasonably well defined by the average vehicle characteristics (within each vehicle class) of today's automobiles/buses, etc.

The initial assessment of the mission definition, power, and power train requirements for each of these vehicles was conducted during the development of the integrated computer model. The purpose of that work was to define the initial requirements for the specific vehicle classes that were to be considered as candidates for FCV power plants. The objective of *this* work is to establish a procedure by which rational analysis of the vehicle sets can be accomplished and to present a vehicle recommendation based on that analysis to DOE's Technical Manager.

The established procedure utilized an initial assessment of the mission definition, thereby defining:

- power and power train requirements for each vehicle type
- vehicle characteristics and configuration (series connected electric power system with regenerative braking and initial drive away capability)
- battery capacity and required drive away performance while the ECE was in start-up mode
- ECE capacity to meet long-term gradeability requirements

This procedure also permitted estimating packaging requirements and location of various components of the power source/power train within the vehicle.

This initial procedure was necessary but not sufficient. More sophisticated simulation methodology was required. The initial definition of the battery size to satisfy drive away requirements and the ECE power to provide gradeability does not guarantee adequate vehicle performance. Following development of the integrated computer simulation code, the vehicles were modeled and compared in more detail to investigate final performance requirements over prescribed driving cycles. The use of the integrated computer simulation code, denoted Vehicle Simulation Model (VSIM), was required to permit iteration on vehicle power source size and, hence, overall vehicle mass to yield the desired performance. VSIM also allows a precise computation of energy usage and vehicle range for each vehicle analyzed.

Different ECE/battery combinations and control strategies were considered to maximize vehicle performance while minimizing driver inconveniences. An analysis method was defined (as described above) and an evaluation matrix established that encompassed the range of control strategies and power train combinations. Combinations were sought that would most closely meet customer performance expectations. Early studies indicated that the optimum control strategy and component sizing combinations might be different for each vehicle category, therefore, the evaluation matrix also considered extreme combinations and control strategies. A more detailed discussion of the analysis methods is presented below.

Required Assumptions

A number of assumptions were made during the vehicle analysis because of the diversity of vehicles and FCV configurations evaluated. These included:

- Vehicle test weight is equal to curb weight plus 136 kg (300 lb) for a driver and a passenger.
- The vehicle does not experience any tire slip during maximum effort straight line accelerations.
- The FCV power train components have a negligible effect on coefficient of drag (C_d) and frontal area.
- Vehicle acceleration compared to the conventional ICE vehicle is not compromised except during the ECE cold start-up time.
- Vehicle range calculations are based on the *EPA highway driving schedule* and the fuel tank capacity.
- Vehicle test weight is constant through the driving cycle.
- The constant accessory load on the FCV provides effectiveness equivalent to ICE powered accessories.
- The vehicle has a single speed transmission.
- The vehicle has a massless converter between the ECE power system and the drivetrain motor that increases the ECE voltage output to the voltage required by the electric drive system.

Simulation Models

The simulation methods used to perform the vehicle simulations consist of a newly developed ECE power source model and a collection of GM proprietary electric vehicle simulation and analysis tools. These tasks include simulation codes as well as static analysis techniques. Many data conversion and graphical analysis programs were also used to aid in the vehicle simulation task. The integration of the power source model with the FCV propulsion simulation code resulted in an FCV analysis capability proprietary to GM and is collectively referred to as VSIM. A diagram of the data flow through VSIM is presented in Figure 4-7. Note that the flow of data is reversed in that road load and acceleration are input variables. The simulation code works backward to define required wheel, drivetrain (including battery), and ECE power inputs. Appropriate losses are considered at each subcomponent. Required ECE input establishes fuel usage while VSIM output yields vehicle fuel economy, energy usage, emissions (when the ECE emissions characteristics are better defined), performance, power train torque, current and voltage, and all other ECE operating parameters such as species flow, temperature, pressures, etc, throughout the ECE power plant. Iterative inputs of road load and acceleration establish the total power train requirements to meet desired performance objectives. Accessories were assumed to be constant at 1-kW.

Under light load conditions (i.e. highway cruise) the ECE power source model was operated at no load until the battery state of charge decreased to a specific minimum level. The ECE power source model was then operated at 15-kW (limited by the battery's ability to accept charge) until the battery state of charge increased to a specific maximum level. At that time, the ECE power source model was again operated at no load. Under heavy load conditions (i.e. maximum acceleration, long-term grade) the ECE power source model was operated at higher power levels up to maximum depending on the demands of the electric drive system and the battery's ability to meet those demands.

ECE Power Source Model

JDC personnel successfully expanded an original LANL code and have modeled the ECE power system operation at predetermined power levels for fixed physical system parameters. The ECE power system model has been updated and modified for use on VAX, HP, and Apple Macintosh computer systems. The ECE code is a chemical engineering system code that solves for steady-state solutions of energy and mass flows in an operating ECE power system. The model is structured to obtain engineering assessments that project ECE component mass, volume, power production, flow rates, temperatures, pressures, and mole fractions throughout the ECE system. Input parameters require that details of some components, such as the polarization curve for the fuel cell stack be specified, however, the code also calculates details of other components such as heat exchangers. One important aspect of this code has been to identify the particular physical arrangement that optimizes system thermal integration, especially the recovery of waste heat from the fuel cell stack that can be effectively used in the fuel processing operation.

The ECE model code has achieved all of the objectives set forth in the program plan except for the introduction of emissions calculations. It was determined that prediction of low level emissions is highly dependent upon the combustor/catalytic convertor design being utilized. Addition of these computations will be implemented when experimental results from the Mark III combustor are available. In all other aspects, key design issues were investigated and the power source design was optimized for use in the integrated model.

The ECE power system operating conditions were mapped as a matrixed set of three-dimensioned (3-D) data algorithms. A series of steady-state operational conditions were calculated, 3-D maps of steady-state performance delineated, and required operational paths to move between these operational plateaus determined. These ECE system data algorithms were then integrated into more general electric vehicle simulation models developed by GMVS. Combining the two codes permits vehicle requirements and power plant operating conditions to be determined over a given driving cycle.

Representative output from the ECE power system modeling code is presented in Figures 4-8, 4-9, and 4-10 and Tables 4-I, 4-II, and 4-III. Typical 60-kW ECE design characteristics are presented in Figure 4-8; these include plots of ECE thermal efficiency and fuel usage rate as functions of power output. Polarization curve characteristics for the entire fuel cell stack are presented in the bottom graph; the 60-kW fuel cell stack is projected to develop 150V at low current density. Full-power conditions result in nearly a 150% intermittent peak power operating condition. The same current density and voltage characteristics have been assumed for the other ECE power sources operating at different power levels.

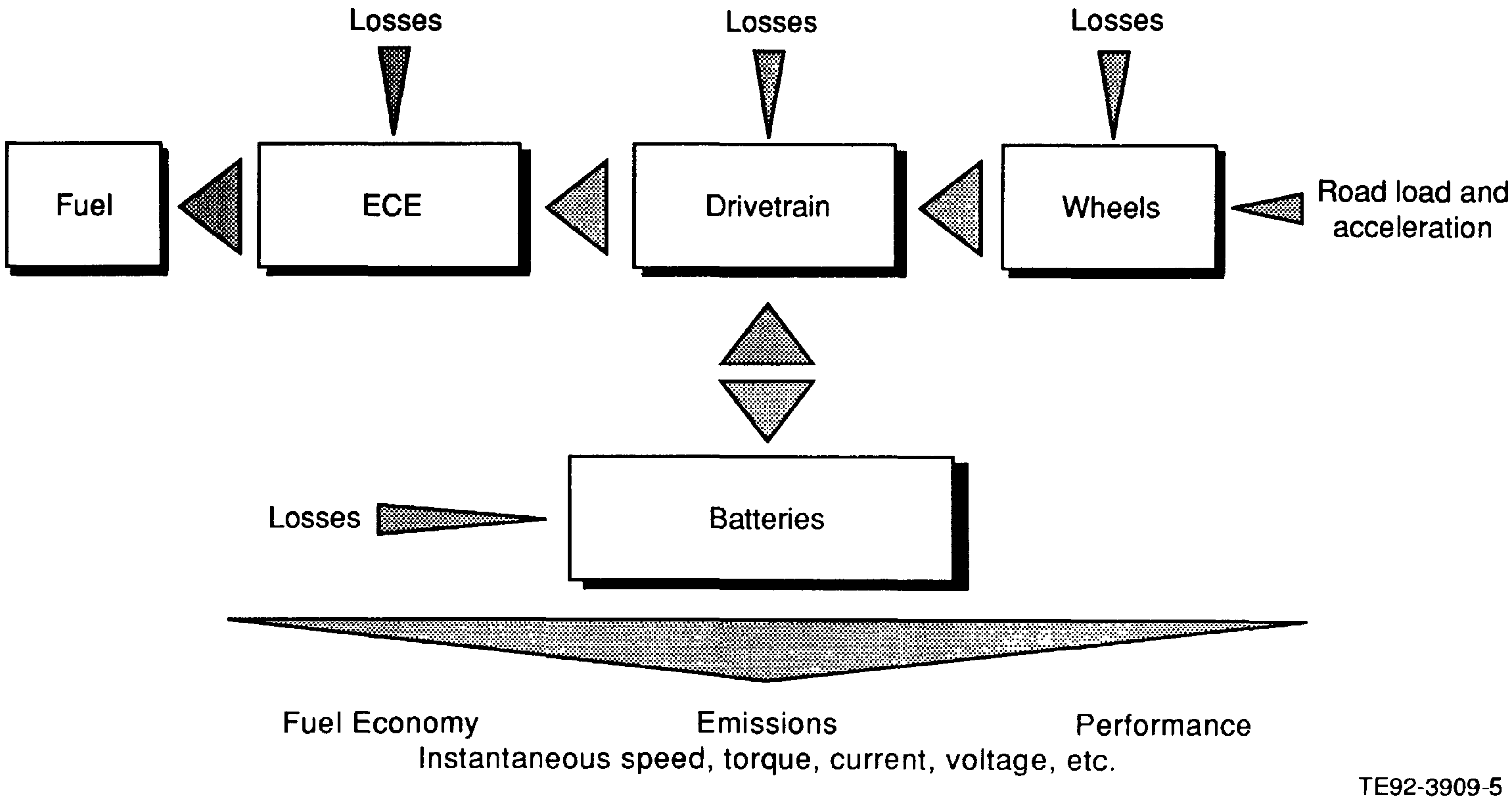


Figure 4-7. VSIM data flow diagram.

Table 4-1.
45-kW ECE off design performance.

ECE elect power output	-10 kW-	-20 kW-	-30 kW-	-40 kW-	-45 kW-
ECE net power output – kW	8.80	17.59	26.27	34.86	39.09
Reformer efficiency	0.7809	0.7791	0.7727	0.7632	0.7605
Fuel cell efficiency	0.7024	0.6704	0.6345	0.5930	0.5691
Overall efficiency	0.5645	0.5378	0.5046	0.4665	0.4448
FC current density – A/cm^2	0.1938	0.4062	0.6437	0.9183	1.0765
FC cell voltage – V	0.8640	0.8246	0.7804	0.7294	0.7000
FC active area – m^2	5.972	5.972	5.972	5.972	5.972
Cell active area – cm^2	464.5	464.5	464.5	464.5	464.5
Current – amps	90.00	188.7	299.0	426.6	500.0
Total volts – V	111.4	106.3	100.7	94.09	90.00
No cells	129	129	129	129	129
FC temperature – C	90	90	90	90	90
Ref temperature – C	230	230	230	230	230
Anode/cath press – Bar	1.5/3.0	1.5/3.0	1.5/3.0	1.5/3.0	1.5/3.0
Cathode stoich –	2.0	2.0	2.0	2.0	2.0
Ref water stoich	1.3	1.3	1.3	1.3	1.3
Fuel flow rate – g/s	0.779	1.634	2.601	3.742	4.391
Water flow rate – g/s	0.569	1.194	1.901	2.735	3.209
Air flow rate – g/s	9.37	19.66	31.25	44.82	52.57
Fuel LHV – kW	15.59	32.71	52.06	74.88	87.89
Burner heat – kW	3.32	7.03	10.42	16.98	20.01
Fuel preheat heat – kW	1.04	2.17	3.45	4.97	5.77
Fuel vapor heat – kW	0.19	0.39	0.62	0.90	1.11
Water vapor heat – kW	1.44	3.03	4.83	6.96	8.18
Reformer heat – kW	1.45	3.05	4.85	6.91	7.74
Reformate cooling – kW	0.41	0.86	1.33	1.81	2.05
Rejection heat – kW	3.85	9.07	16.02	25.61	31.87
Anode/cath HX – kW	0.20	0.46	0.85	1.62	2.18
Compressor power – kW	1.37	2.88	4.58	6.58	7.71
Expander power – kW	0.73	1.59	2.54	3.72	4.44
Fan power – kW	0.38	0.75	1.13	1.52	1.71
Motor power input – kW	1.20	2.41	3.73	5.14	5.91

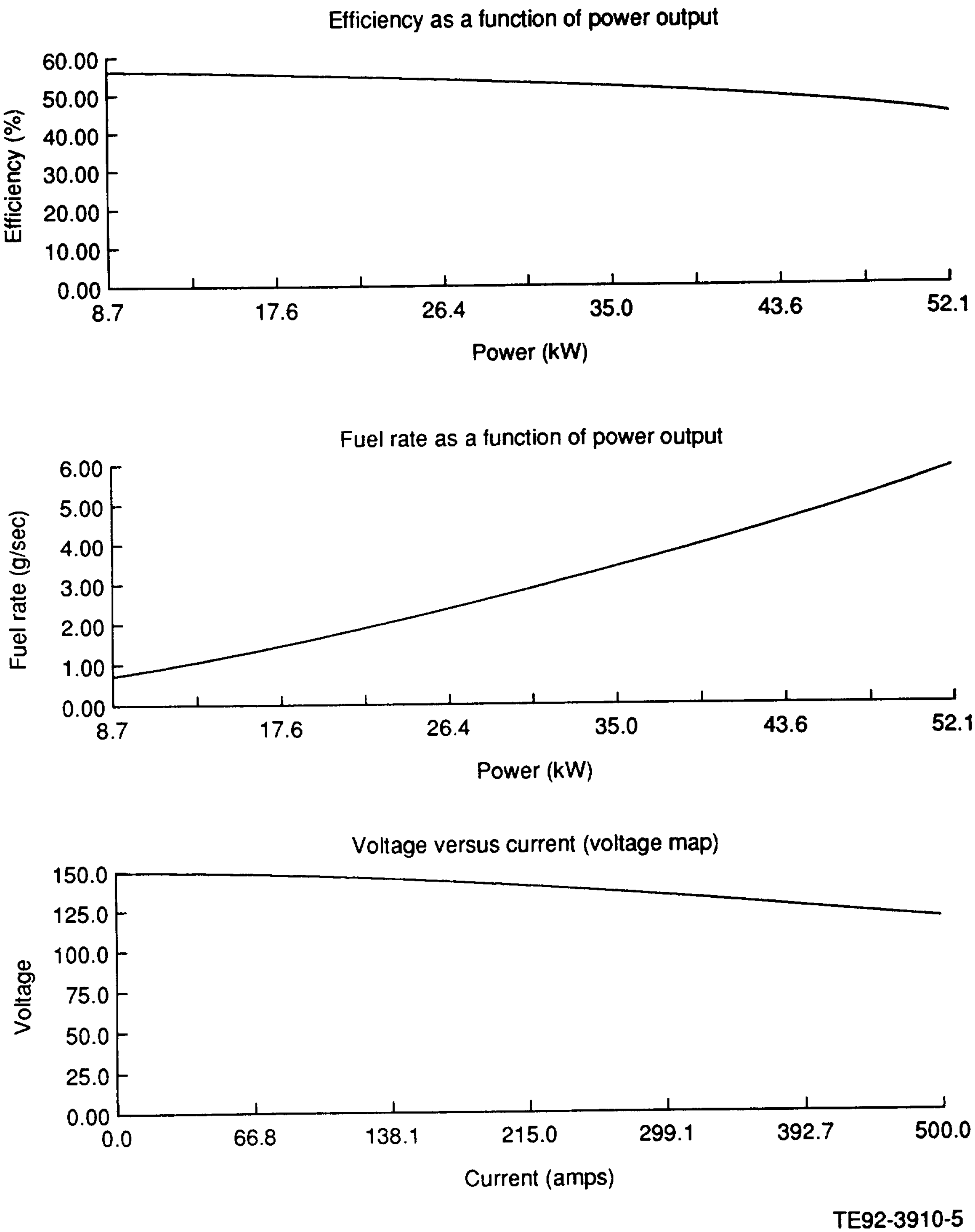


Figure 4-8. 60-kW ECE design characteristics.

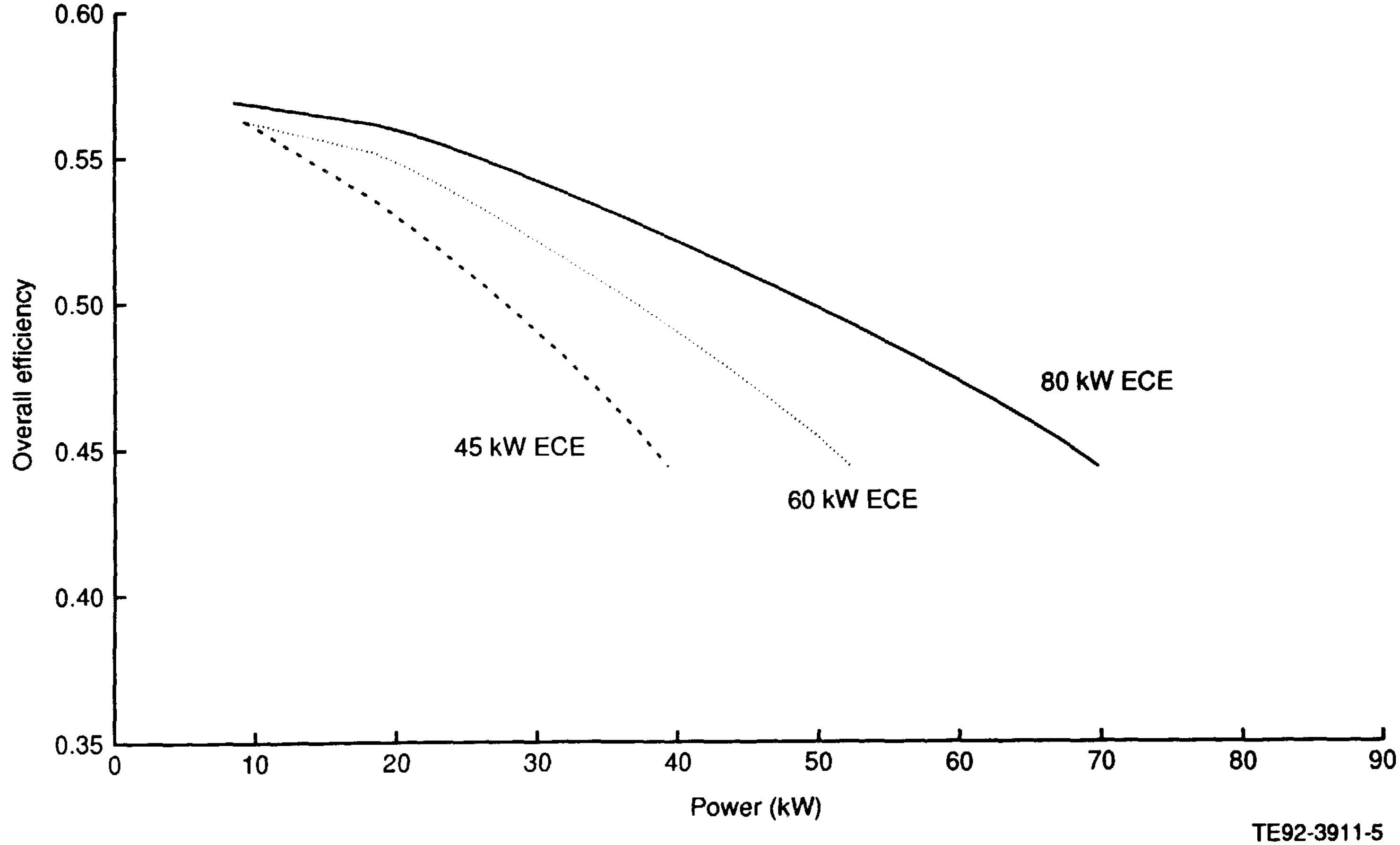


Figure 4-9. Efficiency versus power.

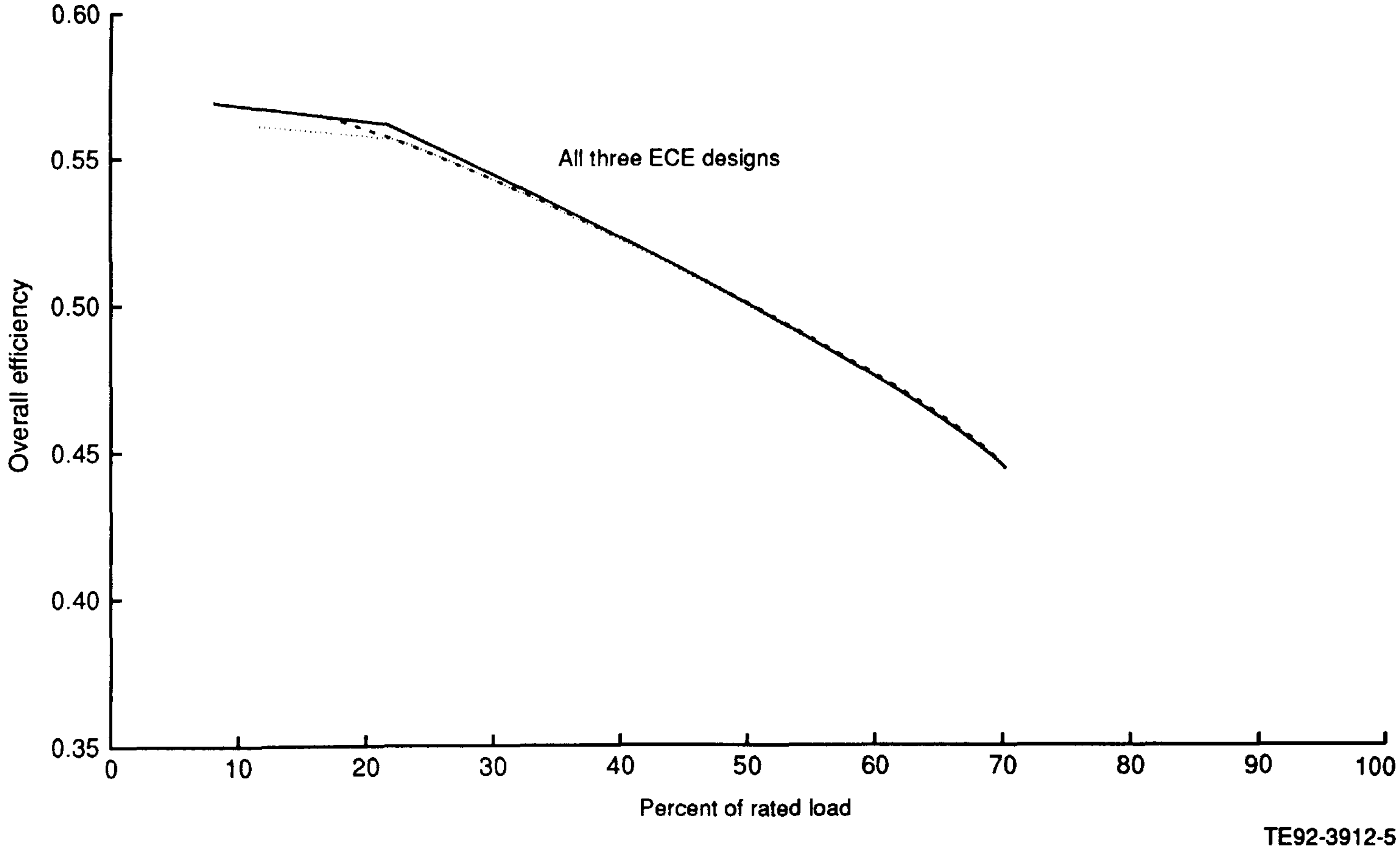


Figure 4-10. Efficiency versus rated load.

Table 4-II.
60-kW ECE off design performance.

ECE elect power output	-10 kW-	-20 kW-	-30 kW-	-40 kW-	-50 kW-	-60 kW-
ECE net power output – kW	8.68	17.62	26.35	35.02	43.62	52.13
Reformer efficiency	0.7737	0.7809	0.7779	0.7746	0.7657	0.7605
Fuel cell efficiency	0.7100	0.6868	0.6618	0.6345	0.6040	0.5691
Overall efficiency	0.5629	0.5522	0.5287	0.5042	0.4764	0.4448
FC current density – A/cm^2	0.1438	0.2974	0.4629	0.6438	0.8453	1.076
FC cell voltage – V	0.8733	0.8448	0.8140	0.7804	0.7429	0.7000
FC active area – m^2	7.962	7.962	7.962	7.962	7.962	7.962
Cell active area – cm^2	465	465	465	465	465	465
Current – amps	68.79	138.1	215.0	299.1	392.7	500
Total volts – V	149.7	144.8	139.5	133.7	127.3	120
No cells	171	171	171	171	171	171
FC temperature – C	90	90	90	90	90	90
Ref temperature – C	230	230	230	230	230	230
Anode/cath press – Bar	1.5/3.0	1.5/3.0	1.5/3.0	1.5/3.0	1.5/3.0	1.5/3.0
Cathode stoich –	2.0	2.0	2.0	2.0	2.0	2.0
Ref water stoich	1.3	1.3	1.3	1.3	1.3	1.3
Fuel flow rate – g/s	0.770	1.594	2.490	3.470	4.575	5.855
Water flow rate – g/s	0.562	1.165	1.820	2.540	3.350	4.279
Air flow rate – g/s	9.26	19.17	29.88	41.66	54.93	70.10
Fuel LHV – kW	15.42	31.91	49.84	69.46	91.57	117.19
Burner heat – kW	3.27	6.83	10.73	15.23	20.93	26.68
Fuel preheat heat – kW	1.02	2.12	3.30	4.61	6.08	7.70
Fuel vapor heat – kW	0.18	0.38	0.59	0.83	1.10	1.48
Water vapor heat – kW	1.43	2.95	4.61	6.44	8.52	10.91
Reformer heat – kW	1.43	2.97	4.63	6.47	8.52	10.32
Reformate cooling – kW	0.41	0.84	1.30	1.78	2.26	2.73
Rejection heat – kW	3.68	8.34	14.21	21.36	30.45	42.50
Anode/cath HX – kW	0.19	0.43	0.72	1.14	1.83	2.90
Compressor power – kW	1.36	2.81	4.38	6.11	8.60	10.28
Expander power – kW	0.61	1.54	2.42	3.39	4.53	5.71
Fan power – kW	0.38	0.75	1.13	1.51	1.89	2.28
Motor power input – kW	1.32	2.37	3.65	4.97	6.38	7.87

Table 4-III.
80-kW ECE off design performance.

ECE elect power output	-10 kW-	-20 kW-	-30 kW-	-40 kW-	-50 kW-	-60 kW-	-70 kW-	-80 kW-
ECE net power output - kW	8.68	17.65	26.41	35.14	43.81	52.44	61.01	69.51
Reformer efficiency	0.7729	0.7821	0.7802	0.7779	0.7745	0.7694	0.7639	0.7605
Fuel cell efficiency	0.7160	0.6986	0.6807	0.6618	0.6416	0.6198	0.5959	0.5693
Overall efficiency	0.5684	0.5632	0.5468	0.5299	0.5110	0.4904	0.4679	0.4449
FC current density - A/cm^2	0.1070	0.2192	0.3374	0.4627	0.5966	0.7410	0.8990	1.076
FC cell voltage - V	0.8810	0.8593	0.8373	0.8140	0.7892	0.7624	0.7330	0.7002
FC active area - m^2	10.62	10.62	10.62	10.62	10.62	10.62	10.62	10.62
Cell active area - cm^2	464.5	464.5	464.5	464.5	464.5	464.5	464.5	464.5
Current - amps	49.70	101.8	156.7	214.9	277.1	344.2	417.6	500.0
Total volts - V	200.8	195.9	190.9	185.6	179.9	173.8	167.1	160.0
No cells	228	228	228	228	228	228	228	228
FC temperature - C	90	90	90	90	90	90	90	90
Ref temperature - C	230	230	230	230	230	230	230	230
Anode/cath press - Bar	1.5/3.0	1.5/3.0	1.5/3.0	1.5/3.0	1.5/3.0	1.5/3.0	1.5/3.0	1.5/3.0
Cathode stoich	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Ref water stoich	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
Fuel flow rate - g/s	0.763	1.566	2.413	3.313	4.283	5.342	6.514	7.805
Water flow rate - g/s	0.558	1.145	1.763	2.482	3.130	3.904	4.748	5.710
Air flow rate - g/s	9.19	18.84	29.02	39.84	51.46	64.10	78.03	93.45
Fuel LHV - kW	15.27	31.34	48.30	66.31	85.73	106.9	130.4	156.2
Burner heat - kW	3.25	6.70	10.35	14.31	18.70	23.72	29.50	35.57
Fuel preheat heat - kW	1.02	2.08	3.21	4.40	5.69	7.09	8.65	10.26
Fuel vapor heat - kW	0.18	0.37	0.57	0.79	1.02	1.28	1.57	1.98
Water vapor heat - kW	1.41	2.90	4.47	6.14	7.95	9.93	12.12	14.54
Reformer heat - kW	1.42	2.92	4.50	6.18	7.98	9.55	12.05	13.76
Reformate cooling - kW	0.40	0.83	1.27	1.73	2.21	2.69	3.17	3.65
Rejection heat - kW	3.57	7.87	12.88	18.95	25.95	34.22	44.22	56.63
Anode/cath HX - kW	0.19	0.42	0.66	0.96	1.36	1.91	2.76	3.87
Compressor power - kW	1.35	2.76	4.26	5.85	7.55	9.40	11.45	13.71
Expander power - kW	0.60	1.51	2.34	3.22	4.18	5.25	6.46	7.83
Fan power - kW	0.38	0.75	1.13	1.51	1.89	2.27	2.65	3.04
Motor power input - kW	1.32	2.35	3.59	1.86	6.19	7.56	8.99	10.49

The overall thermal efficiency for three different ECE power sources as a function of net power output is presented in Figure 4-9. As expected, if the efficiency of the three ECEs is presented as a function of normalized percent rated load, the characteristics of each ECE appears similar as indicated in Figure 4-10.

Finally, the ECE operating condition data were tabulated, mapped, and input into VSIM as the sets of data algorithms appearing in Tables 4-I, 4-II, and 4-III. The 45-kW, 60-kW, and 80-kW power sources were analyzed for this report, and 50-kW operating conditions for the urban transit bus were interpolated.

ECE Power Source Model Integration With Electric Vehicle Propulsion Model-VSIM

Integration of the ECE power source and hybrid electric vehicle simulation model represents the main effort of Task 1.1. The GM electric vehicle simulation model is oriented towards power train and vehicle requirements and contains sophisticated battery/motor simulation options. The simulation model itself is considered proprietary by GM, but results obtained through its use were used to satisfy the requirement of this report.

The final version of this integrated model, denoted VSIM, yields projected system performance, fuel efficiency, and detailed system operating conditions (current densities, reactant inlet and exit temperatures, fuel and oxidant usage, battery state-of-charge, etc) of the power source and power train components in candidate vehicles over a driving cycle. In combination with design analysis, results from the model can be used to verify preliminary sizing and packaging concepts of the total propulsion system and drivetrain components and determine the effect of powerplant installation on vehicle design and performance.

The method of using VSIM is readily apparent in Figure 4-11. Data that are required as input to VSIM are depicted on the left hand portion of the figure. The vehicle simulation model then produces the required outputs of energy usage, performance, and emissions (when appropriate) as depicted on the right hand side of the figure. A sample 60-kW computer input to VSIM using the data algorithms described above is presented in Table 4-IV. Sample outputs from VSIM appear in Figures 4-12 and 4-13. The average vehicle power delivered to the road and vehicle velocity as functions of time during a typical FUDS driving cycle are presented in Figure 4-12 for a similar performance mini-van. Velocity profile (0 to 96.6 km/hr) characteristics as a function of time for the same vehicle are presented in Figure 4-13.

Vehicle Component Packaging Estimates And Constraints

All power train components are expected to fit within the vehicle body and chassis system. The conceptual vehicle designs were based on conventional vehicles with currently available and accepted construction methods and materials. Although some designers have indicated that current vehicle weight may be reduced by 10% over the next decade, *this was not taken into account in the current work.*

Component Sizing

Consistent component sizing methods were developed in order to compare and evaluate the different vehicles being analyzed. Component sizes were approximated based on a linear relationship between mass, volume, and power output capability. Allowances in mass and volume were made to allow for support structure, wiring, and additional hardware for each component. The assumed component mass and volume relationships are presented in Figures 4-5 and 4-6.

The components in the urban bus were assumed to be the same as those calculated and presented in the DOE Fuel Cell/Battery Powered Bus Systems report.

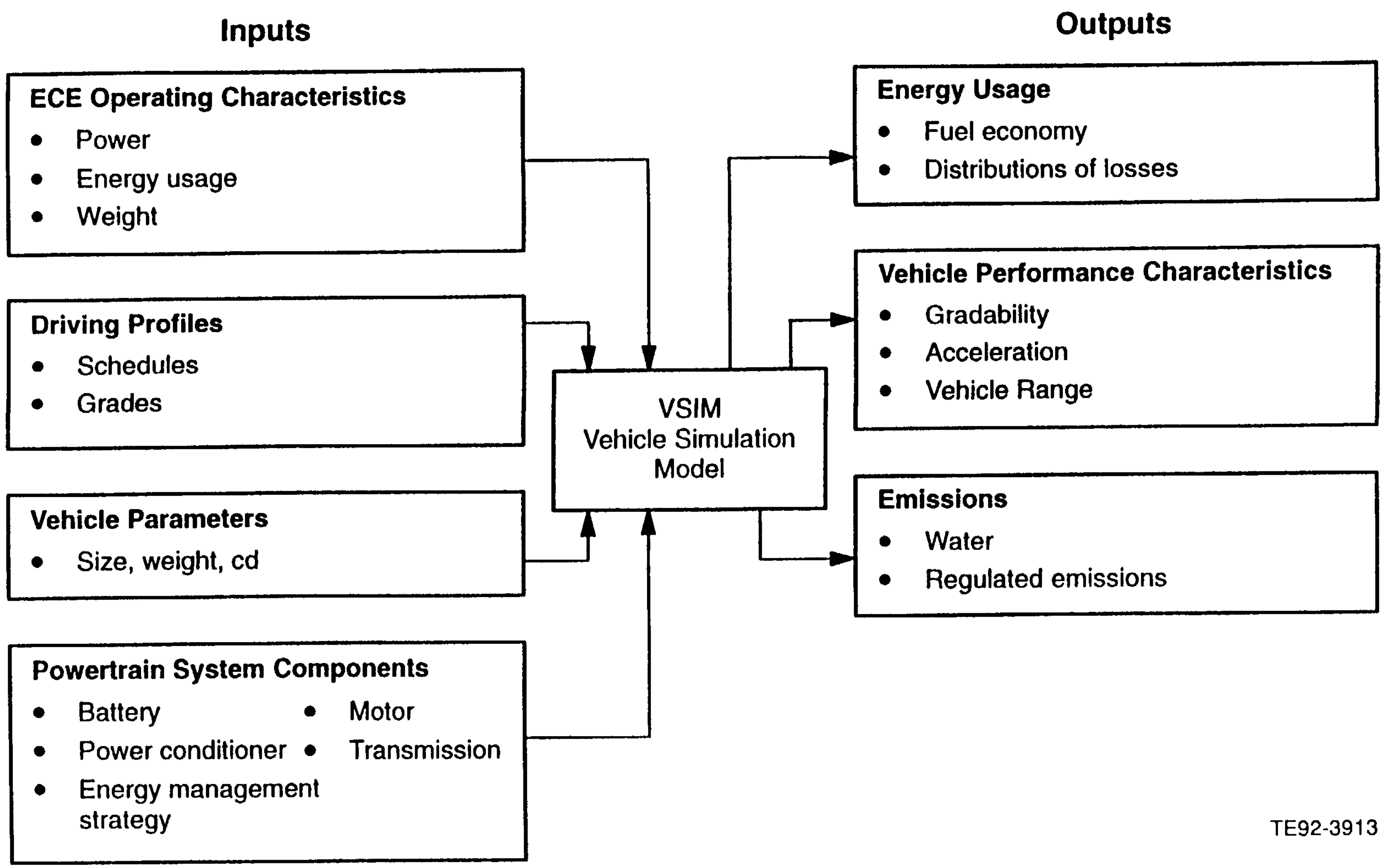


Figure 4-11. VSIM data flow.

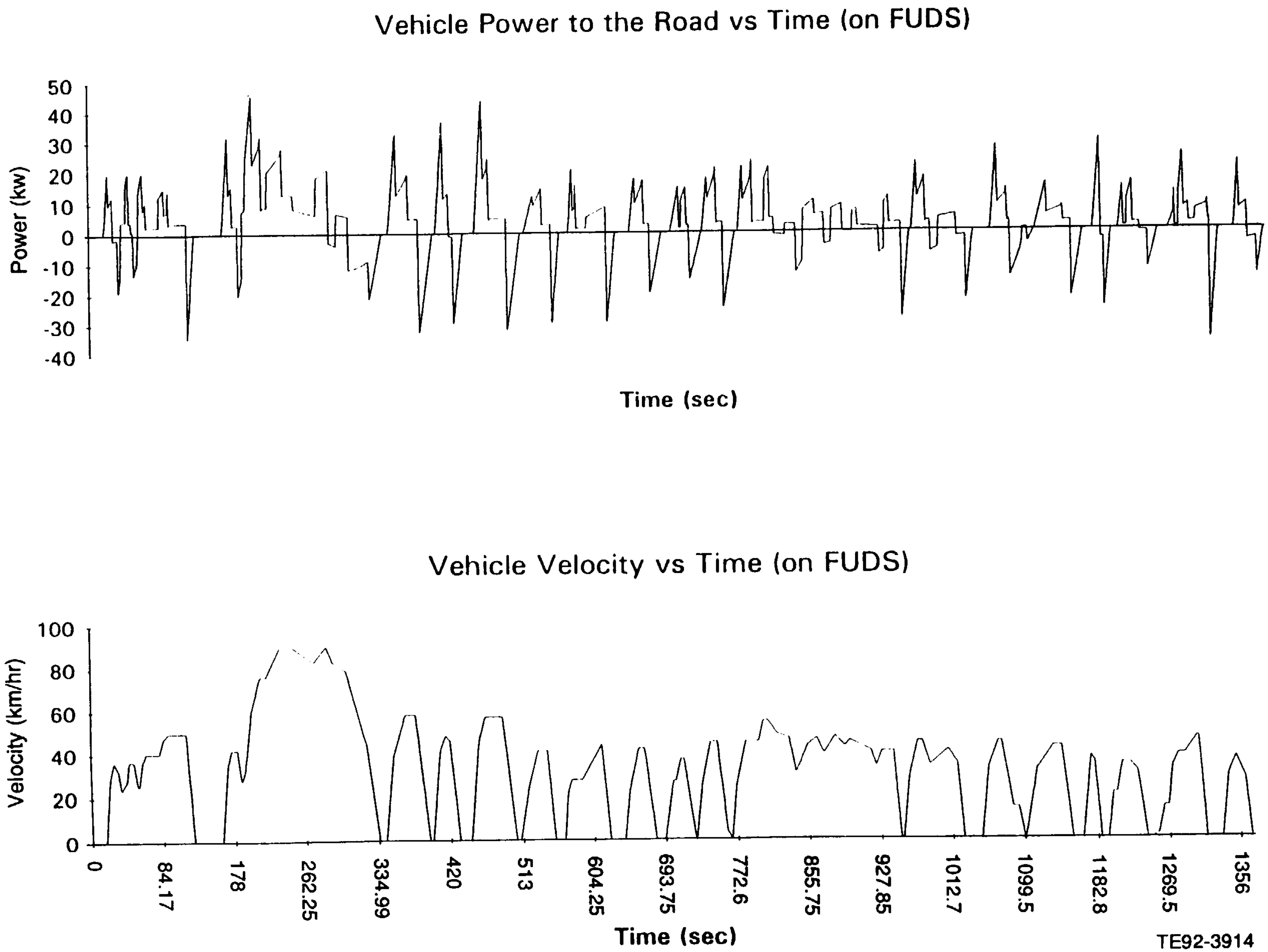


Figure 4-12. Vehicle perfomance on FUDS.

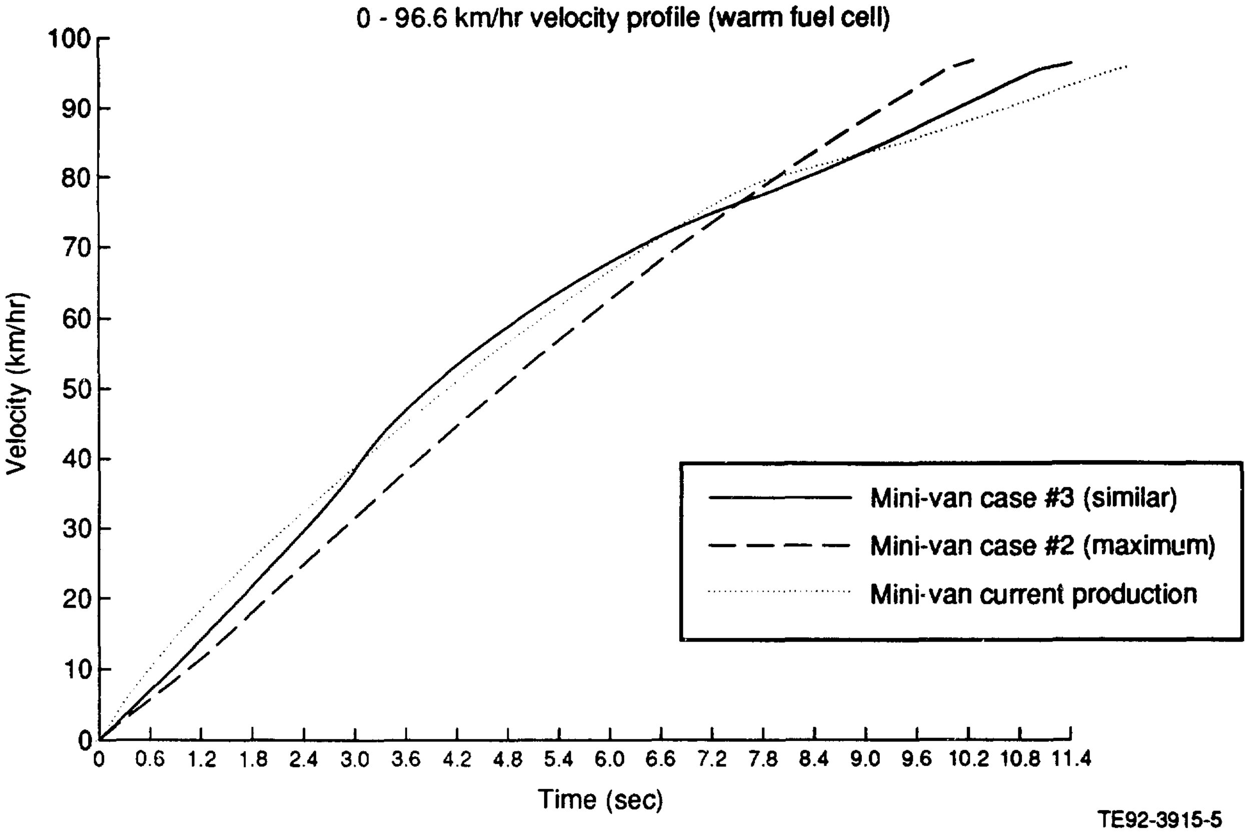


Figure 4-13. 0 to 96.6 km/hr velocity profile (warm ECE).

Table 4-IV.
Sample 60-kW computer input to VSIM.

```
{file:C:\ELECTRIC\FUEL CELL\FC.EDF}
60-kW Fuel Cell (Electro Chemical Engine) Jan, 1992
6       Number of different Voltages
2       Number of different Currents at each Voltage
---------------------------------------
1.0000      Voltage scale
1.0000      Current and fuel rate scale
---------------------------------------
2.8499312537E+03     dEA[1] CUR = EA[1] + dEA[2]*V + dEA[3]*V**2 + dEA[4]*V**3
-2.7481258763E+01    dEA[2] (Current vs Voltage Curve)
9.1831173885E-02     dEA[3]
-2.1673903086E-04    dEA[4]
66.79 138.1 215.0 299.1 392.7 500.0
149.7 144.8 139.5 133.7 127.3 120.0
---------------------------------------
-3.8666665457E-02    dEB[1] FR = EB[1] + dEB[2]*P + dEB[3]*P**2 + dEB[4]*P**3
8.0770767046E-02     dEB[2] (Fuel Rate vs Power Curve)
```

-63849201505E-05 dEB[3]
5.9074073620E-06 dEB[4]
0.770 1.594 2.490 3.470 4.575 5.855
10.0 20.0 30.0 40.0 50.0 60.0

0.077	1.0		Min Power Fuel rate rate (g/sec); Min Power (kW);
16.7	16.7		(+) Transient (%RL/sec),(-)Transient (%RL/sec);
120.0	150.0		Min Allowable Voltage,Max Allowable Voltage;
60.0	167.5		Max power (kW) & associated voltage;
500.0	120.0		Max current (Amps) & associated voltage;
149.7	66.79	0.77	Voltage, Current, Fuel rate g/s @ best Power to Fuel consumption
120.0			Starting Time (s)

149.7 Volts

Current (Amps)	Fuel Rate (g/sec)	Efficiency (%)
66.79	0.770	56.29
66.80	0.771	56.30

144.8 Volts

Current (Amps)	Fuel Rate (g/sec)	Efficiency (%)
138.10	1.594	55.22
138.11	1.595	55.23

139.5 Volts

Current (Amps)	Fuel Rate (g/sec)	Efficiency (%)
215.00	2.490	52.78
215.01	2.491	52.79

133.7 Volts

Current (Amps)	Fuel Rate (g/sec)	Efficiency (%)
299.10	3.470	50.42
299.11	3.471	50.43

127.3 Volts

Current (Amps)	Fuel Rate (g/sec)	Efficiency %
392.70	4.575	47.64
392.71	4.576	47.65

120.0 Volts

Current (Amps)	Fuel Rate (g/sec)	Efficiency %
500.00	5.855	44.48
500.01	5.856	44.49

Accessories and Tanks (Fuel and Water Storage)

Accessories for an FCV would include all systems necessary to meet the minimum comfort and safety requirements of current vehicles. Accessories differ from those of conventional ICE vehicles to the extent that there is no mechanical or vacuum power available to drive them. In the driving cycle simulation, accessory loads were assumed to be constant at 1-kW, electrically driven, and hence, represent a parasitic loss to the ECE/battery output just as they do to the output of an ICE.

Also, for purposes of this evaluation, the fuel and water storage containers were considered to be thin walled (possibly stainless steel or carbon fiber) and require minimum space and mass in addition to the methanol and water specified to be onboard the vehicle.

Vehicle Packaging Constraints

Packaging considerations were necessary to ensure that the electric power train would fit within the vehicle body and chassis system. System components included the ECE, batteries, inverter, electric motor, fuel tank, and accessories (HVAC, power steering, etc). The space allocated within the vehicle for these components was located under-hood, under-trunk, under-body (van only), and within the trunk/cargo area. The size, shape, and location of the volumes available were different for each of the vehicles considered. The general location and dimensions of the available volumes within the vehicles being considered are illustrated in Figures 4-14 through 4-17. A consistent packaging strategy was developed to locate components within the body and chassis. This strategy was similar to the methods of the JPL Advanced Vehicle Systems Assessment Study. The guidelines are as follows:

- Front wheel drive was maintained, which meant that the motor and inverter must be located in the under-hood area.
- The under-hood area was utilized first.
- The under-trunk area (cars only) and the under-body area (vans and urban bus only) was utilized primarily for battery storage.
- Locating the ECE in the under-trunk and under-body locations was avoided in order to protect the components.
- The trunk/cargo area was utilized for all hybrid power train components that could not be packaged in the above listed areas.
- The fuel tank location was restricted to under-trunk or under-body.

Component locations for the urban bus were taken from the layout drawings outlined in the DOE Fuel Cell/Battery Powered Bus Systems report.

Table 4-V contains a summary of the packaging volumes available for the conceptual vehicle packaging evaluations.

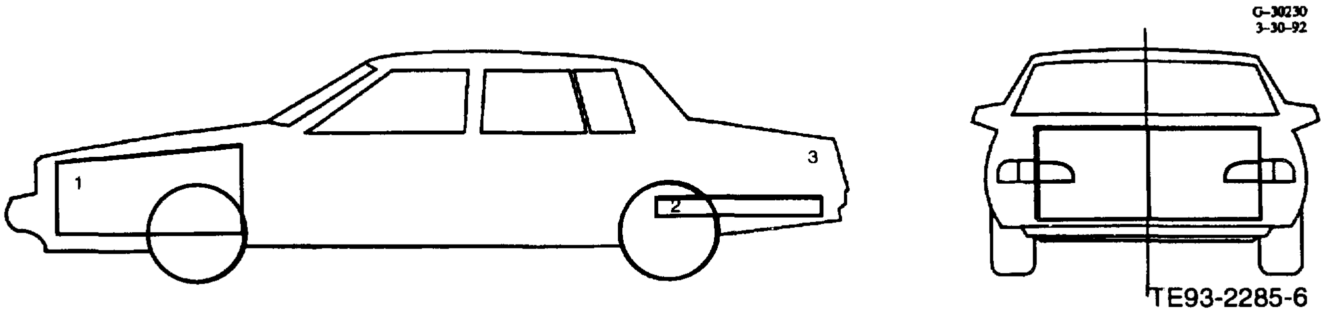
Table 4-V.
Conceptual vehicle packaging volumes available.

EPA Classification	Large Car		Mid-Size Car		Compact Car		Mini-Van	
Packaging volumes available	m^3	ft^3	m^3	ft^3	m^3	ft^3	m^3	ft^3
Under hood	0.761	26.87	0.580	20.54	0.350	12.36	0.676	23.87
Under trunk (including fuel tank)	0.102	3.61	0.171	6.03	0.120	4.24	0.111	3.92
Fuel tank area	0.068	2.40	0.063	2.21	0.575	2.03	0.076	2.67
Under body	None	None	None	None	None	None	1.000	35.31
EPA volumes								
Trunk/cargo	0.513	18.1	0.447	15.8	0.368	13.0	0.521	18.4
Passenger	3.036	107.2	2.880	101.7	2.639	93.2	4.148	146.5
Total EPA volume	3.548	125.3	3.299	116.5	3.007	106.2	4.669	164.9

VEHICLE EVALUATION PROCEDURE AND CRITERIA

The following procedures were used during the vehicle evaluation to determine vehicle characteristics, specifications, and performance.

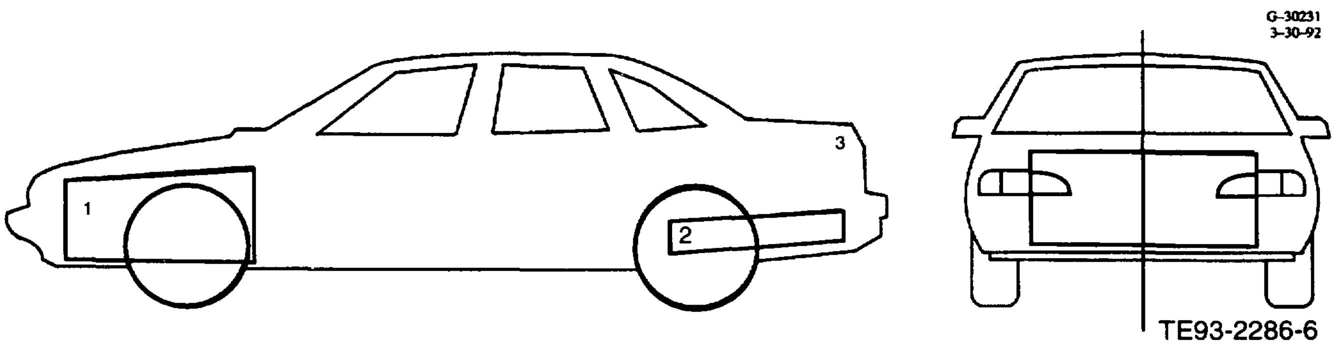
1. Select a battery size based on the initial vehicle weight to meet the selected performance requirement during the ECE cold start-up period. As described previously, and summarized below, the "selected performance requirement" when the ECE is not operating may constitute cold-start performance equivalent to a conventional vehicle or simply that required to meet the relatively moderate acceleration demands of the FUDS cycle. The former performance requirement requires a larger battery pack. This may affect ECE power system requirements because of the added weight.
2. Size the ECE power system based on vehicle gradeability requirements and performance expectations.
3. Combine the ECE and battery in the conceptual ICE vehicle and model the vehicle performance using the VSIM program. Evaluate the modeled performance compared to the desired performance.
4. Iterate starting at procedure 1 until the vehicle is able to meet its performance requirements with the proper component masses included.
5. Package the power train components within the designated packaging locations permitted by the vehicle packaging constraint criteria. Some vehicles will not have sufficient room to package the components within the designated locations, these vehicles were found to sacrifice passenger compartment space.
6. Size the fuel tank based on available space or use the equivalent size of the similar conventional ICE vehicle, whichever is less. Vehicle range is determined by fuel tank capacity and fuel consumption during the EPA highway driving schedule. As the FCVs use methanol, conventional passenger cars use gasoline, and urban transient buses use diesel fuel, fuel economy for the purpose of determining range is best expressed as km/L (mpg).



Dimension:	Average Height (cm)	Average Length (cm)	Average Width (cm)	Volume (m^3)
Under Hood	54.87	113.79	121.90	0.761
Under Trunk	8.13	101.60	121.90	0.102

TE92-3916

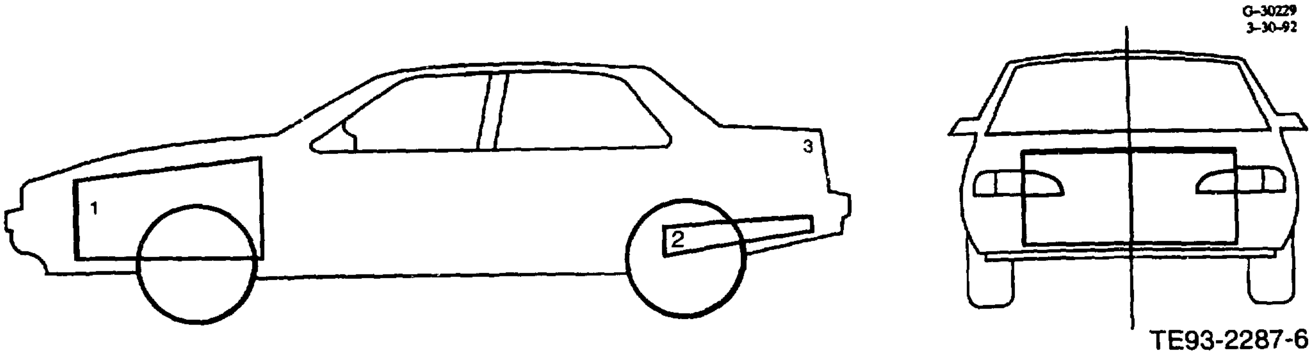
Figure 4-14. Large car vehicle dimensions.



Dimension:	Average Height (cm)	Average Length (cm)	Average Width (cm)	Volume (m^3)
Under Hood	48.16	100.30	120.40	0.580
Under Trunk	16.05	88.29	120.40	0.171

TE92-3917

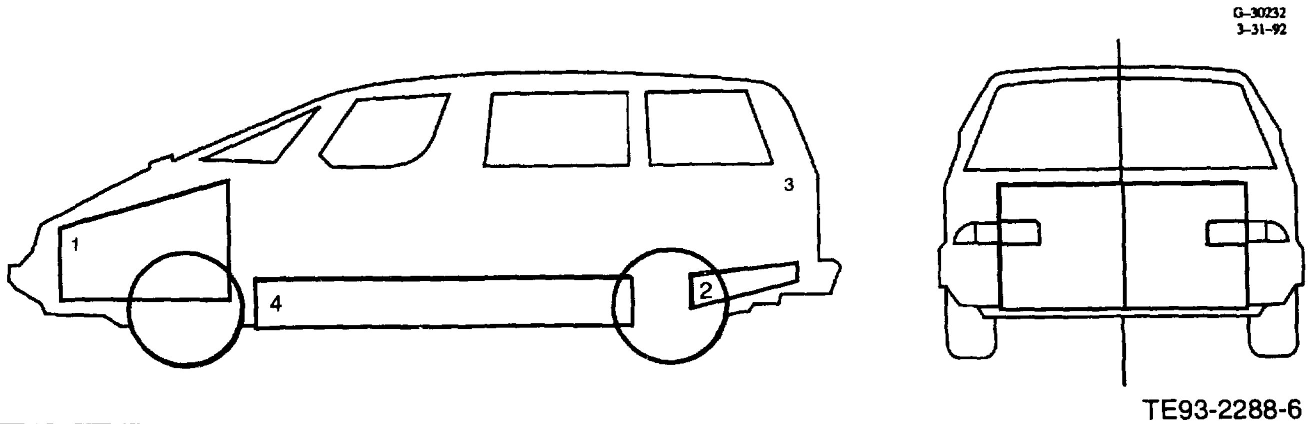
Figure 4-15. Mid-size car vehicle dimensions.



Dimension:	Average Height (cm)	Average Length (cm)	Average Width (cm)	Volume (m^3)
Under Hood	35.35	90.00	110.00	0.350
Under Trunk	14.00	78.00	110.00	0.120

TE92-3918

Figure 4-16. Compact car vehicle dimensions.



Dimension:	Average Height (cm)	Average Length (cm)	Average Width (cm)	Volume (m^3)
Under Hood	55.62	96.41	126.09	0.676
Under Body	33.37	237.61	126.09	1.00

TE92-3919

Figure 4-17. Mini-van vehicle dimensions.

Evaluation Matrix

After careful consideration of the six criteria above, an evaluation matrix was established to guide the vehicle analysis. The vehicle analysis evaluation matrix used to control the number of analyses performed is presented in Table 4-VI. FCV design, performance, component sizing, and fuel economy were analyzed only for those cases denoted.

- **Current Production Vehicle** This specification includes the design and performance criteria of the current production ICE vehicles listed in the Current Vehicle Design and Performance Comparisons of Section III. The results are used as the reference for the FCV in the same class. In the case of the urban bus, the production vehicle specifications are those of the PAFC ECE bus performance projections from earlier DOE work. Some of the bus comparisons include the current production diesel powered bus upon which the PAFC ECE bus is based.

- **Maximum Performance FCV** The performance requirement of this control strategy is that acceleration not be compromised when compared to the reference ICE vehicle even during the ECE cold start-up period. This requires additional batteries that add mass to the vehicle. The ECE is sized to meet the long-term gradeability requirements. A larger ECE is generally required because of the increased vehicle mass. As a result of the power train component sizing methods used, this vehicle demonstrates better acceleration than the reference vehicle once the ECE is warmed-up and operational.

- **Similar Performance FCV** The performance requirement of this control strategy is to meet the relatively moderate acceleration demands of the FUDS cycle exclusively on battery power during the ECE cold start-up period. The ECE is again sized to meet long-term gradeability requirements.

- **Urban Bus ECE/Battery Combination** This evaluation specification included the design and performance criteria for the urban transit bus evaluation. All power train components were identical to those specified in the DOE Fuel Cell/Battery Powered Bus Systems report and replace the

Table 4-VI.
Vehicle analysis evaluation matrix.

Reference vehicle:	Large Car	Mid-Size Car	Compact Car	Mini-Van	Urban Bus
Control strategy	1992 Cadillac Fleetwood	1992 Buick Regal	1992 Chevrolet Cavalier	1992 Chevrolet Lumina	Diesel and PAFC Bus
Current production vehicle	•	•	•	•	•
Maximum performance PEM ECE/battery combination	•	•	•	•	
Similar performance PEM ECE/battery combination	•	•	•	•	
Urban transit bus PEM ECE/battery combination					•

PAFC ECE with the PEM ECE. Evaluations were based on volume, mass, and fuel consumption comparisons.

- **ECE Only Powered Vehicle** The concept of evaluating an ECE vehicle with no batteries was considered. However, the ECE capacity needed to meet the driving requirements was deemed to be volume prohibitive for the projected PEM ECE technology. Another problem facing this configuration was that the ECE start-up period is projected to be longer than 20 seconds. Start-up and drive away times greater than 20 seconds for noncommercial vehicle classes are considered to be unacceptable.

VEHICLE EVALUATION AND COMPARISON

This section summarizes the results of computations performed for each of the vehicles under consideration. The evaluation matrix and vehicle evaluation procedures were described in the previous section. All performance and energy analysis results were obtained using the integrated VSIM model. Specifications and results are presented for each vehicle considered in separate tables located in Appendix D. Each table contains major data blocks of specific parameters which are incorporated in the evaluation analysis and subsequent comparison ranking of the vehicles. Each of these major data blocks is described below. Refer to any table in Appendix D for information pertaining to the layout of the data blocks or specific information contained within them.

- **Vehicle Data** This data block lists the vehicle EPA classification and overall physical characteristics and specifications.

- **Performance** This data block describes the acceleration, gradeability, and operational results that were either previously determined (for current vehicles) or calculated by VSIM for proposed FCV use.

- **EPA Volumes Available** This data block contains the passenger, trunk/cargo, and fuel tank available volumes after the power train and fuel tank were located in the vehicle.

  The total volume available for the urban transit bus was not calculated due to lack of information from the DOE Fuel Cell/Battery Powered Bus Systems report, but it was assumed to have the same size as the diesel powered bus.

- **Energy Usage** This data block presents the fuel economy values that were known or calculated for the vehicle when operated on the EPA FUDS and FHDS. Published (sticker) fuel economy values were used for the current production ICE vehicles. The simulation results for the FCVs were adjusted per EPA regulations in order to make valid comparisons (see Appendix B). A composite energy usage for each vehicle, in kW-hr/km, is also presented in this data set. These values were obtained based on the weighting factors specified in CAFE calculations for that vehicle and the energy content of the fuel being used (see Appendix B for details). FCV results are also compared to the reference vehicle. A comparison of energy usage by reference and proposed FCV passenger vehicles is also presented in Table 4-VII for each of the EPA vehicle classifications being considered.

  The fuel economy for the PEM ECE urban transit bus was calculated and presented in kg/hr (fuel used at rated load) to be consistent with the previous DOE Fuel Cell/Battery Powered Bus System report for the PAFC ECE.

Table 4-VII.
A comparison of energy usage by current and proposed FCV passenger vehicles.

	Fuel Economy (km/L / mpg)			Energy Usage (KW-hr/km)		
	FUDS	FHDS	Composite	FUDS	FHDS	Composite
Large Car						
Reference	6.80/16.0	10.64/25.0	8.13/19.1	1.313	0.840	1.100
Maximum performance FCV	6.29/14.8	7.46/17.6	6.76/15.9	0.696	0.586	0.648
Difference from reference	-8%	-30%	-17%	-47%	-30%	-41%
Similar performance FCV	7.94/18.7	8.85/20.8	8.33/19.6	0.551	0.496	0.526
Difference from reference	17%	-17%	3%	-58%	-41%	-52%
Mid-Size Car						
Reference	8.06/19.0	11.90/28.0	9.43/22.2	1.105	0.750	0.946
Maximum performance FCV	6.54/15.4	8.40/19.7	7.25/17.1	0.669	0.523	0.603
Difference from reference	-19%	-30%	-23%	-39%	-30%	-36%
Similar performance FCV	8.06/19.0	9.90/23.4	8.85/20.8	0.543	0.441	0.496
Difference from reference	0%	-16%	-6%	-51%	-41%	-48%
Compact Car						
Reference	10.20/24.0	14.93/35.0	11.90/28.0	0.875	0.600	0.751
Maximum performance FCV	9.52/22.5	11.76/27.8	10.42/24.6	0.458	.0371	0.419
Difference from reference	-6%	-21%	-12%	-48%	-38%	-44%
Similar performance FCV	11.11/26.1	12.99/30.4	11.90/27.9	0.395	0.339	0.370
Difference from reference	9%	-13%	0%	-55%	-44%	-51%
Mini-Van						
Reference	7.63/18.0	9.80/23.0	8.47/20.0	1.167	0.913	1.053
Maximum performance FCV	6.58/15.5	8.26/19.5	7.25/17.1	0.665	0.529	0.604
Difference from reference	-14%	-15%	-15%	-43%	-42%	-43%
Similar performance FCV	7.52/17.7	9.17/21.5	8.13/19.2	0.583	0.480	0.537
Difference from reference	-2%	-7%	-4%	-50%	-48%	-49%

- **Components** In this data block, the required power, weight, volume, and intended location of the powerctrain components are presented. Component sizing and packaging were accomplished by the guidelines described in the Vehicle Packaging Constraints section. A visual representation of the vehicle and the general packaging layout is displayed at the top of each table.

Discussion of Results and Vehicle Comparison The expected performance for each of the vehicles within a given criterion, with the exception of the urban bus, is presented in Figures 4-18 through 4-23. These criteria were also used to compare the vehicles and arrive at a composite ranking. The recommendation of an FCV for further study was primarily influenced by this composite ranking (Section V).

The 0 to 96.6 km/hr acceleration time for each vehicle is compared in Figure 4-18. Because of the definitions employed in the sizing of the power train, the "maximum performance" (MP) vehicles attain target speed in the same time as the reference vehicle when the ECE is in the start-up (cold) mode. If the ECE is fully operational, these vehicles accelerate faster than the production vehicle because of the additional power available from the ECE. In contrast, the "similar performance" (SP) vehicles have significantly degraded acceleration during the ECE warm-up. This is expected because they have

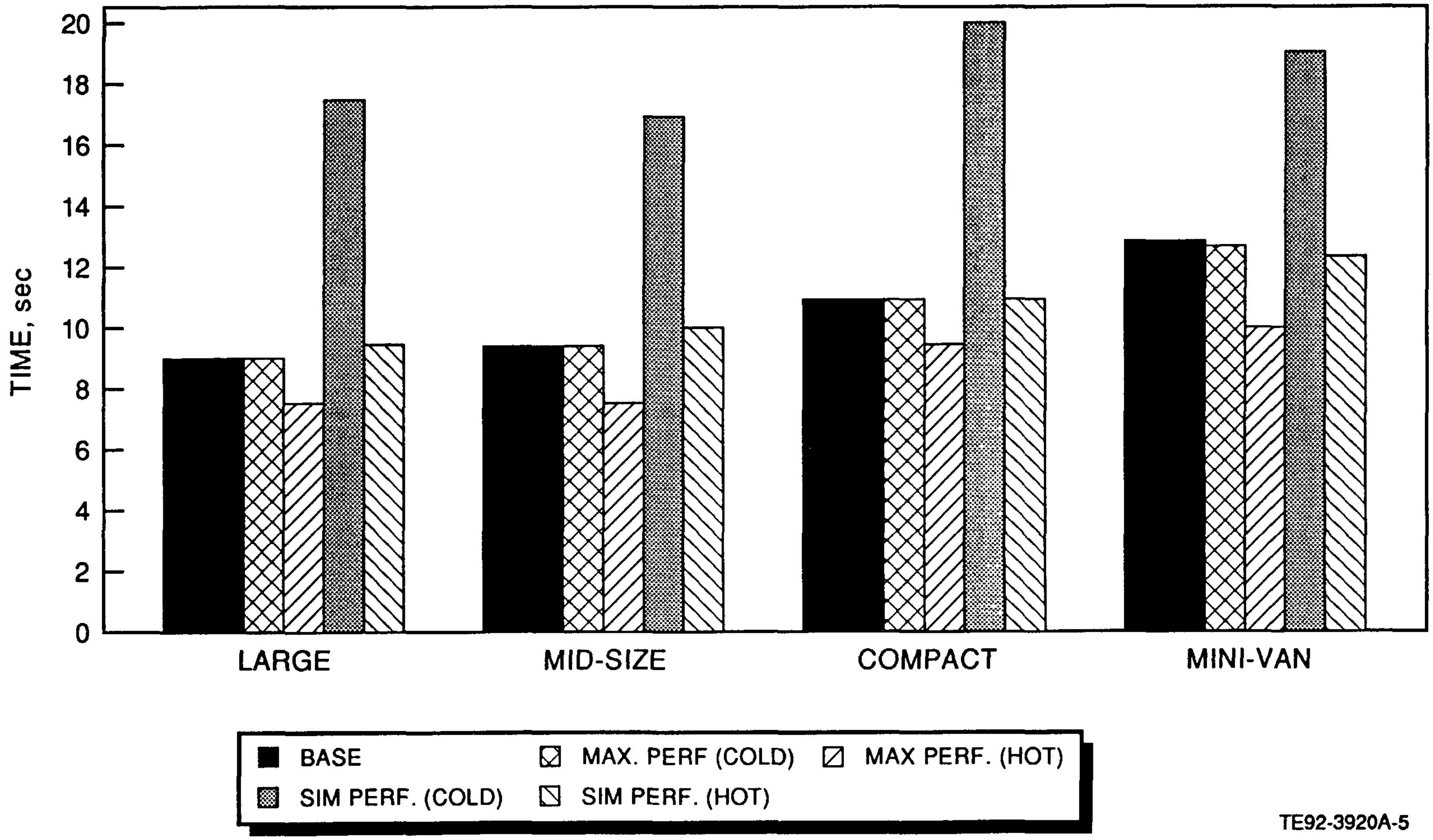


Figure 4-18. 0 to 96.6 kph (60 mph) performance comparison.

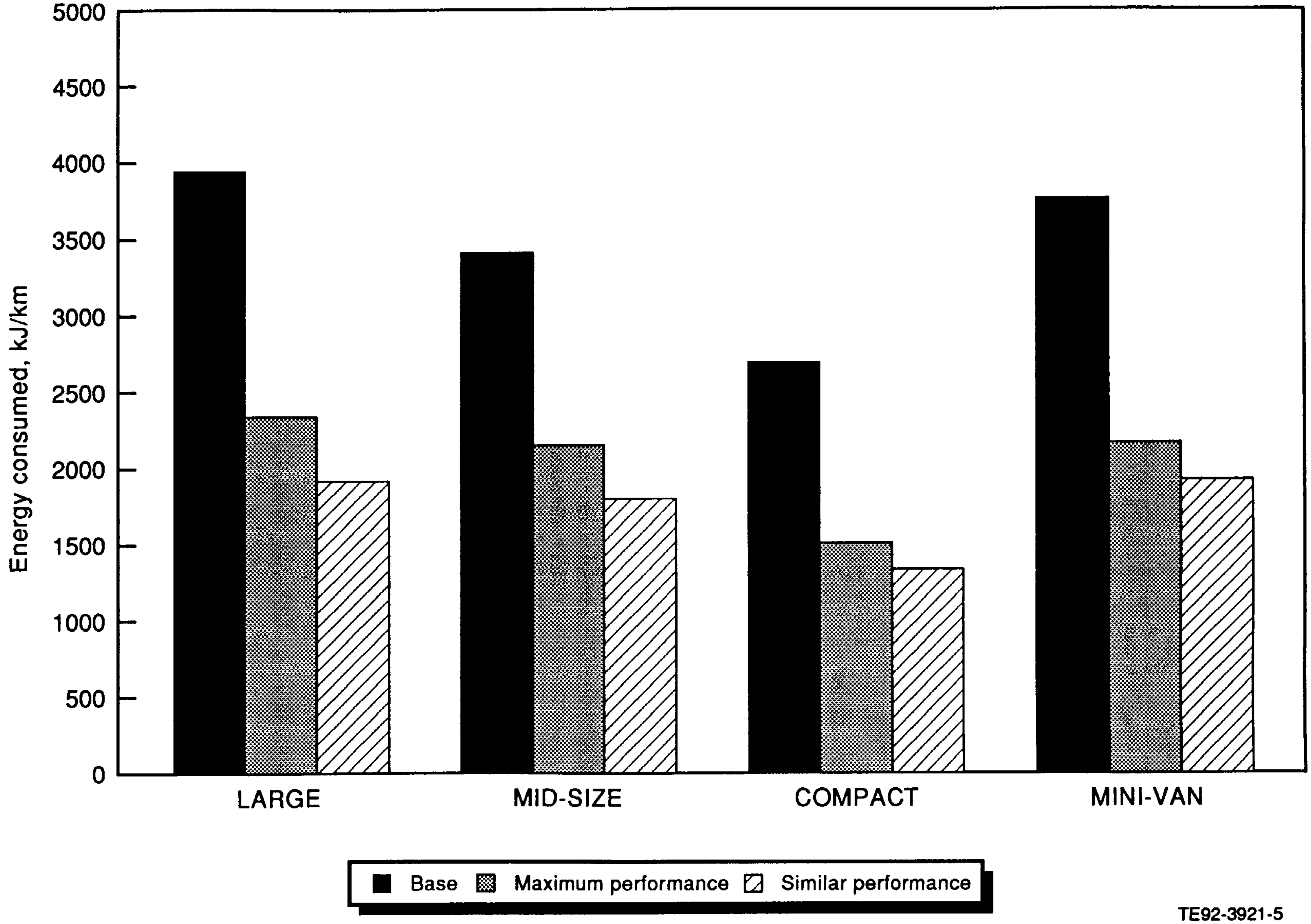


Figure 4-19. Vehicle composite (55/45) energy usage.

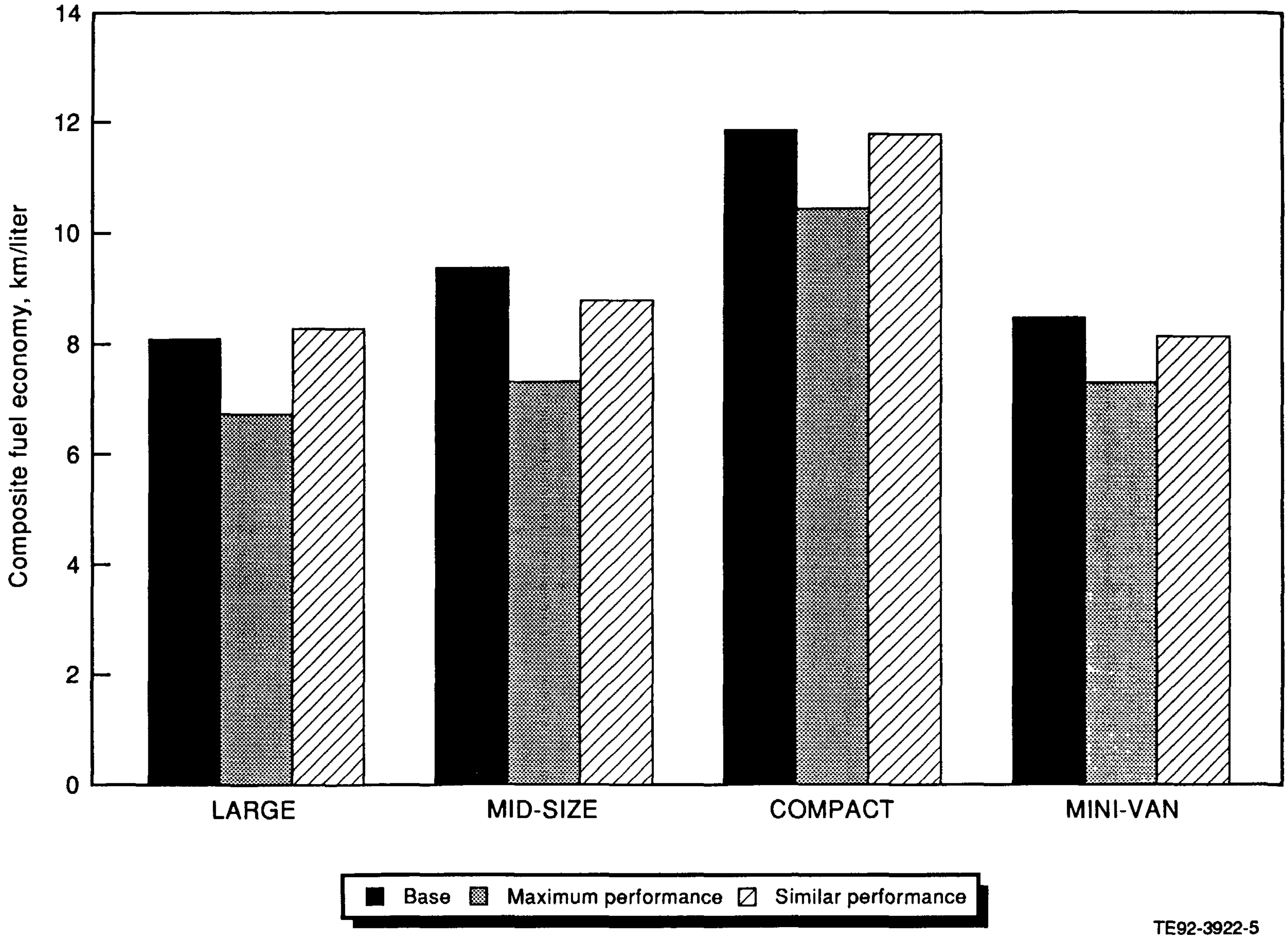


Figure 4-20. Vehicle composite (55/45) fuel economy estimate.

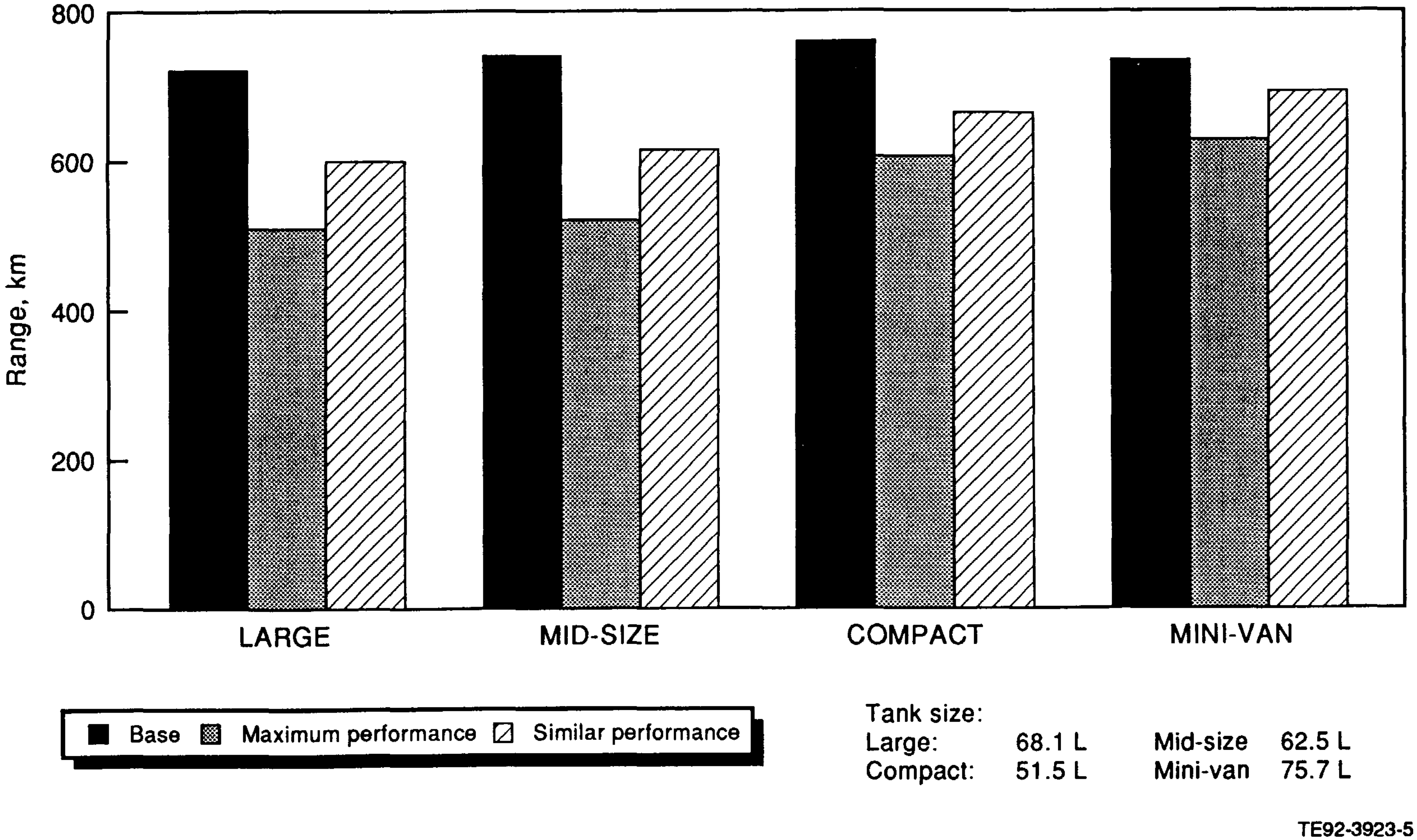


Figure 4-21. Estimated highway range on FHDS.

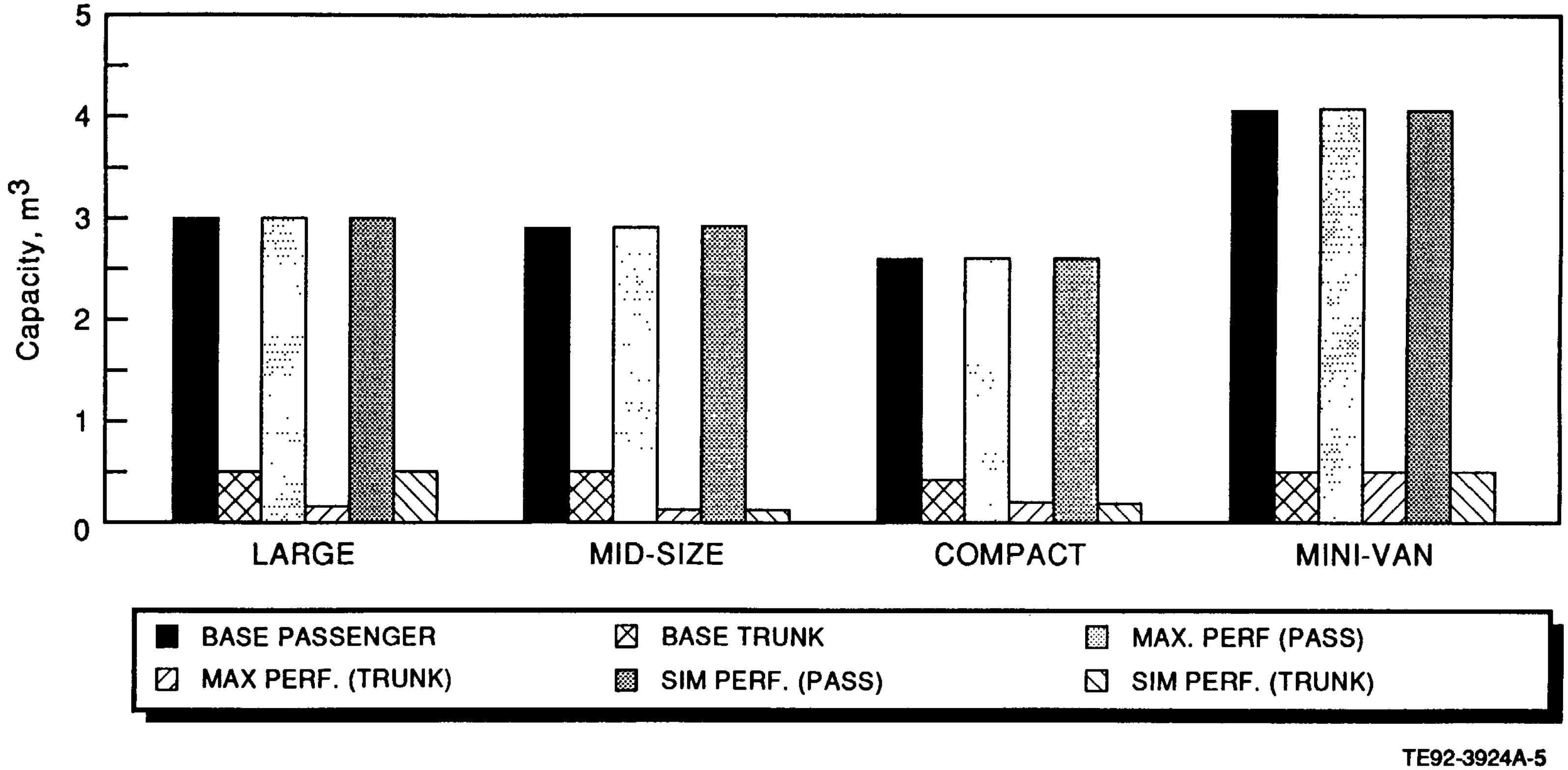


Figure 4-22. EPA volumes available.

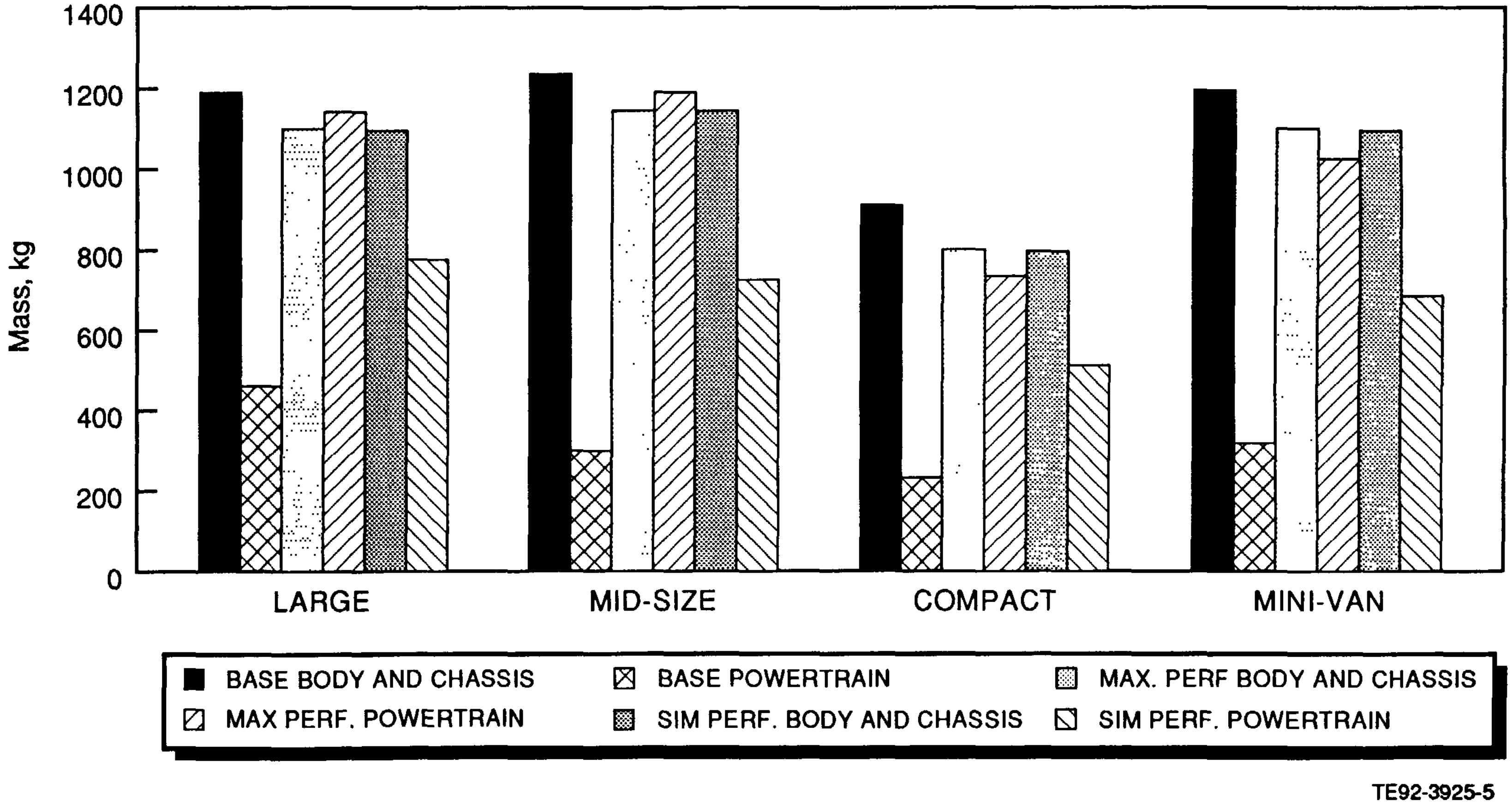


Figure 4-23. Vehicle curb mass comparison.

a reduced battery inventory. After the ECE is warmed-up, their acceleration is comparable to the reference vehicles.

Composite energy consumption is displayed in Figure 4-19 for each vehicle. The superior thermal efficiency of the ECE is explicitly reflected by these data. Each of the SP vehicles consume only about half the energy of their production counterparts. Because of their increased mass, the MP vehicles consume more energy than do the SP vehicles, but they still show a significant advantage over the reference vehicles.

The data presented in Figures 4-20 and 4-21 is indicative of the fuel mileage that a customer might expect. Composite fuel economy, calculated by the weighting procedure prescribed for CAFE purposes is presented in Figure 4-20. The SP vehicles generally show values comparable to or slightly less than the production vehicles, while the MP vehicles are inferior. Since the FCVs are fueled with methanol, which has noticeably lower energy content than gasoline (Appendix B), it is to be expected that the composite mileage results would appear as in Figure 4-20. If the current ICE production vehicles were also fueled with methanol, the highway composite mileage would be reduced by nearly one-half.

Since all of the vehicles within a class have the same tank volume, the methanol consuming FCVs are not able to travel as far as their gasoline fueled counterparts (Figure 4-21). The amount of energy which the FCVs capture through regenerative braking is reduced on the FHDS. As a result, their energy efficiency advantage is not as great in highway as in urban driving. These factors combine to produce reduced highway range for all the FCVs. It should be noted, however, that if the production vehicles were fueled with methanol, the results would be drastically different.

An important factor in considering alternate power train concepts is the degree to which their generally higher power train component volumes can be packaged in a vehicle. The extent to which the FCV power train intrudes into the available cargo space for each of the vehicles is depicted in Figure 4-22. While the results vary somewhat from one vehicle class to another, there is generally reduced usable space for each of the passenger cars. This is not the case for the mini-van because the power train could be partially placed under the vehicle floor, a location which was not allowed for the passenger cars. None of the FCV power trains required any intrusion into the passenger compartment. It should be recognized that this may not hold true when a detailed design is complete, but these results are valid for the vehicle recommendation purposes of Task 1.2.

Curb mass of the various vehicles is presented in Figure 4-23. All of the ECE vehicles are heavier than the production ICE versions, the MP vehicles particularly so. The deleterious effect of the increased mass on energy consumption is mitigated by the ability of the FCVs to use regenerative braking energy.

V. VEHICLE RECOMMENDATION AND REMAINING ISSUES

VEHICLE COMPOSITE RANKING

Each of the candidate FCVs is ranked in each of five categories as shown in Table 5-I. The five categories are considered to be the most relevant results from the analysis of Section IV and are:

- operating temperature ECE acceleration performance
- cold ECE acceleration performance
- composite energy consumption
- EPA trunk/cargo volume available
- range on the FHDS

A composite ranking for each vehicle was calculated based on the results in each category and is presented in Table 5-I and Figure 5-1. The ranking in each category (columns) was based on a relative comparison of FCV candidate to the current production reference vehicle. The comparison is considered equivalent if the FCV results were within 2% of the reference vehicle results. When this is the case, the FCV results are denoted by an E for equivalency. The numerical rankings were established such that a candidate FCV that met or exceeded the reference values in any category received a value of 1. The remaining FCVs were then ordered according to their ranking relative to the reference ICE vehicle and assigned values beginning with 2, etc. The rankings in each category were then combined (summed) in each row determining the composite rank for that candidate FCV. The FCV candidate that compared most favor-

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Table 5-I.
FCV analysis summary comparison to reference vehicle.

	0 to 96.6 km/hr (60 mph) Performance		Composite Energy Consumption	EPA Trunk/Cargo Volume Available	Range on FHDS	Composite Ranking
Maximum Performance Case	Cold	Hot				
Large	E	82%	59%	25%	70%	5.0
Mid-Size	E	84%	64%	29%	70%	5.2
Compact	E	87%	56%	49%	79%	4.4
Mini-Van	E	84%	57%	E	85%	2.8
Similar Performance Case						
Large	193%	107%	48%	93%	83%	4.0
Mid-Size	187%	111%	53%	29%	84%	5.6
Compact	182%	E	49%	58%	87%	3.6
Mini-Van	158%	95%	51%	E	94%	2.4
Transient Urban Bus Similar Performance Case						
PEM Urban Bus	NA	91%	52%	92%*	NA	3.7
PAFC Urban Bus	NA	91%	68%	88%*	NA	6.0

E = Equivalent (within ±2% of reference vehicle performance)
* = Percentage of Full Seating Capacity Available

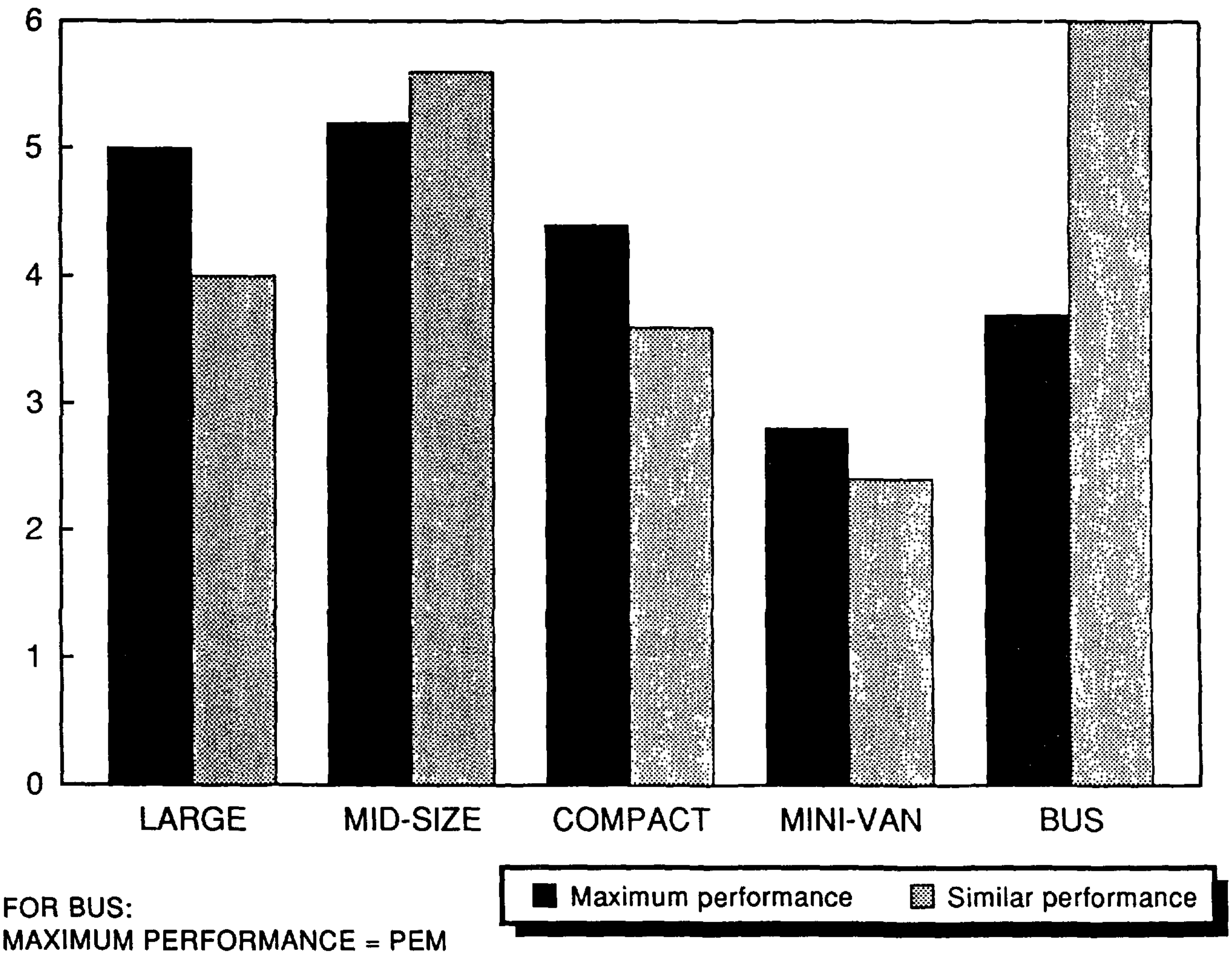
ably with the current production ICE vehicle has the lowest overall numerical value and, hence, the highest composite ranking.

The PAFC and PEM ECE conceptual urban bus results were compared to a similar diesel powered reference bus so that the performance of a PEM ECE could be compared against both that of a PAFC ECE and that of a diesel power plant.

The composite rankings of the candidate vehicles are presented in both Figure 5-1 and Table 5-I. Recall that the lowest numerical value reflects the highest composite rating, and therefore, the candidate vehicle most likely to become a successful FCV.

VEHICLE RECOMMENDATION

The output of Task 1.2 is a candidate vehicle recommendation for further study in Task 1.3. The vehicle recommendation and selection method followed the mission definition and performance evaluation cri-



FOR BUS:
MAXIMUM PERFORMANCE = PEM
SIMILAR PERFORMANCE = PA

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Figure 5-1. Composite ranking.

teria that were the bulk of the project effort in Task 1.2. The recommendation was based on compliance to performance objectives, achievement of high vehicle efficiency, and packaging constraints.

Based on the FCV evaluation criteria and composite ranking method discussed above, the vehicle classifications are ranked from most to least suitable FCV candidates as follows:

1. Mini-Van, similar performance
2. Mini-Van, maximum performance
3. Compact Car, similar performance
4. PEM Urban Bus, maximum performance
5. Large Car, similar performance
6. Compact Car, maximum performance
7. Large Car, maximum performance
8. Mid-Size Car, maximum performance
9. Mid-Size Car, similar performance
10. PAFC Urban Bus, similar performance

A more detailed explanation of the configuration and performance of the top three FCV candidates follows.

1. **Mini-Van, Similar Performance** This vehicle is similar in size to a current production Chevrolet APV. All of the hybrid power train components are mounted under the hood and under the body with no intrusion into the passenger or cargo area. This vehicle exhibits somewhat sluggish acceleration during the first few minutes of operation before the ECE is warmed-up to operating temperature. Once the ECE is at temperature, this FCV meets current reference vehicle performance specifications. The energy usage is estimated to be only 51% of the equivalent current production ICE mini-van.

2. **Mini-Van, Maximum Performance** This vehicle is identical in size and interior volume to the similar performance mini-van. However, the vehicle acceleration matches the current reference vehicle acceleration when the ECE is cold and exceeds the current reference vehicle acceleration when the ECE is at operating temperature. The energy usage is estimated to be 57% of the equivalent current production ICE mini-van. The energy usage is higher for this FCV than the similar performance mini-van due to the increased weights of the battery pack and ECE.

3. **Compact Car, Similar Performance** This vehicle is similar in size to a current production Chevrolet Cavalier with all of the power train components mounted under the hood and in the trunk, but with no intrusion into the passenger area. This vehicle also exhibits somewhat sluggish acceleration during the first few minutes of operation before the ECE is warmed-up to operating temperature. Once the ECE is at temperature, this FCV meets current reference vehicle performance specifications. The energy usage is estimated to be only 49% of the equivalent current production ICE compact car. The penalty of power train intrusion into the trunk of this vehicle complicates power train installation and impacts customer satisfaction.

REMAINING ISSUES

A number of future R&D issues were identified during the course of Task 1.2. These issues need to be addressed before an FCV can become practical. Some of the issues also pertain directly to other types of electric vehicles. Many of the battery related issues listed may be addressed by the USABC. The issues are presented by system, but in no particular order.

Vehicle

- vehicle accessories
- component packaging
- overall power train control
- powertrain component costs
- mass

Batteries

- size
- mass
- cost
- power density
- cold performance
- cycle life
- safety
- long-term battery terminal corrosion
- environmental impact

Electrochemical Engine

- size
- mass
- cost
- fuel cell stack voltage (now requires step-up converter)
- start-up time
- transient response
- real-world operational considerations (road vibration, owner maintenance, cold weather, long-term storage)

Electric Drive System

- size
- mass
- cost
- one ratio versus two ratio transmission

VI. NOMENCLATURE

A	amperes
AAMA	American Automobile Manufacturers Association
ac	alternating current
AIAM	Association of International Automobile Manufacturers
A/ft^2	amperes per square foot
BTU	British thermal unit
°C	degrees centigrade
C_d	coefficient of drag
CH_3OH	methanol
cm	centimeter
cm^2	square centimeter
cm^3	cubic centimeter
CO	carbon monoxide
CO_2	carbon dioxide
CRC	Coordinating Research Council
Cu	copper
CuO	copper oxide
DAKO	DAKO Services Incorporated
dc	direct current
DOE	Department of Energy
DOT	Department of Transportation
ECE	electrochemical engine
EPA	Environmental Protection Agency
°F	degrees fahrenheit
FCV	fuel cell vehicle
FHDS	Federal Highway Driving Schedule
ft	foot
ft^2	square foot
ft^3	cubic foot
FUDS	Federal Urban Driving Schedule
g	grams
gal	gallons
GM	General Motors
GMVS	General Motors Vehicle Systems
gpm	gallons per minute

H_2	hydrogen
H_2O	water
HP	horsepower
hr	hour
Hz	hertz
ICE	internal combustion engine
in.	inch
in.^{2}	square inch
in.^{3}	cubic inch
JDC	Joint Development Center
JPL	Jet Propulsion Laboratory
kg	kilograms
kJ	kilo-joule
km	kilometer
km/hr	kilometers per hour
km/L	kilometers per liter
kW	kilo-watt
kW-hr	kilo-watt hour
LANL	Los Alamos National Laboratory
L	liter
lb	pound
m	meter
m^2	square meter
m^3	cubic meter
M85	85% methanol/15% gasoline
mA	milliampere
mA/cm^2	milliamperes per square centimeter
mi	miles
ml	milli-liter
mpg	miles per gallon
MP	maximum performance
mph	miles per hour
NA	not available or not applicable
O_2	oxygen
PAFC	phosphoric acid fuel cell
PEM	proton-exchange membrane
%	percent

PROX	preferential oxidation unit
Pt	platinum
R&D	research & development
rpm	revolutions per minute
scfm	standard cubic feet per minute
sec	seconds
SOC	state of charge
SP	similar performance
TASC	The Analytical Sciences Corporation
TiB_2	titanium diboride
ULEV	ultra-low emission vehicle
UMTA	Urban Mass Transportation Administration
USABC	United States Advanced Battery Consortium
V	volts
VSIM	vehicle simulation model
WBS	work breakdown structure
W-hr/kg	Watt-hour per kilogram
W/kg	Watts per kilogram
ZEV	zero emission vehicle
ZnO	zinc oxide

APPENDICES

Appendix A

Compilation of Current Vehicle Design and Performance Specifications (Tabular and Graphical Presentation)

Vehicle Specifications Spreadsheet

**numbers in italics are estimated*

		Automobiles							
Vehicle Identification									
Vehicle #	1	2	3	4	5	6	7	8	9
Year	1992	1992	1992	1992	1992	1992	1991	1992	1992
Manufacture	Chevy	Buick	Lincoln	Ford	Chevy	Buick	Ford	Cadillac	Cadillac
Model	Cap. 4D	RdMst 4D	TownCar	LTD CV	Cap. Wg.	RdMst wg	CV Wgn	Brougham	Fleetwood
Vehicle Class	Large	Large	Large	Large	Large	Large	Large	Large	Large
Design Specification									
* Curb Weight (lbs.)	3952	4073	3871	3693	4278	4468	4028	4164	3642
* GVM (lbs.)									
* Weight Distribution (% Front)	56	*55*	*50*	*55*	*50*	*50*	*50*	*50*	63
* Wheel Base (in)	116	116	117	114	116	116	114	122	114
* Overall Length (in)	214	216	219	212	217	218	216	221	208
* Overall Width (in)	77	78	77	78	80	80	79	77	73
* Frontial Area (Ft^2)	25.8	*25.9*	*26.0*	*25.8*	*26.6*	*25.9*	*25.9*	*25.8*	*25.0*
* Drag Coefficient	0.31	*0.33*	*0.35*	*0.35*	*0.31*	*0.33*	*0.35*	*0.35*	0.42
Shadow Area (Ft^2)	114	117	117	115	120	121	119	117	106
* Engine Size (liters)	5	5.7	4.6	4.6	5	5	5	5	4.9
* Net Horsepower (HP)	170	180	190	190	170	170	150	170	200
* Torque (Ft.-lbs.)	255	300	260	260	255	255	270	255	275
* Number of Passengers	6	6	6	6	8	8	6	6	6
* Fuel Tank Size (gal.)	23	23	20	20	22	22	18	25	18
* Oil Capacity (qt.)	4	5	6	5	4	4	5	4	5
* Coolant (Water) Capacity (qt.)	17	18	14	14	17	17	14	17	12
Tire Size									
* Width (mm)	225	*225*	*215*	*225*	225	*225*	*225*	*225*	205
* Aspect Ratio	70	*75*	*70*	*70*	75	*75*	*70*	*75*	70
* Rim (in.)	15	15	15	15	15	15	15	15	15
Component Weight Estimates									
* Engine Dressed-Measured (lbs.)									
Engine Dressed-Estimated (lbs.)	625	713	575	575	625	625	625	625	613
* Transmission & Convertor-Measured (lbs.)									
Transmission & Convertor-Estimated (lbs.)	190	217	175	175	190	190	190	190	185
Fuel & Tank Weight-Estimated (lbs.)	169	169	147	147	161	161	132	183	132
Oil Weight (lbs.)	8	9	9	9	8	8	9	8	9
Coolant Weight (lbs.)	39	41	32	32	39	39	34	40	28
Cooling System Components Wgt.-Est. (lbs.)									
Powertrain Weight-Estimated (lbs.)	1030	1148	938	938	1023	1023	990	1046	968
EPA									
* EPA Volume Index (Ft.^3)	134.6	116	140.3	131.9	170.1	*170.1*	*165*	128	125.3
* Trunk Volume (Ft.^3)	20.4	20	22.3	20.6	54.7	*54.7*	*50*	20	18.1
Passenger Volume (Ft.^3)	114.2	96	118	111.3	115.4	115.4	115	108	107.2
* EPA Highway Mileage (MPG)	26	25	24	25	26	25	24	25	25
* EPA City Mileage (MPG)	17	17	17	18	16	16	17	18	16
Performance									
* 0 - 60 MPH (96.6 KPH)(sec.)	9.7	9.7	10.2	*10*	12.6	*12.6*	*10*	9.4	*8.7*
* 30 - 60 MPH (sec.)	6.3	*5*	*5*	*5*	*5.5*	*5.5*	5	*5.7*	*4*
* 50 - 70 MPH (sec.)	7.4	*7*	*7*	*7*	*7*	*7*	*7.3*	7	*6*
* 1/4 Mile Elapsed Time (sec.)	17.4	17.3	17.5	16.9	18.1	*18.1*	*17.4*	17.1	*16*
* Top Speed (MPH)	108	*110*	*105*	105	110	*110*	*105*	105	*112*
Average Accelerations									
0 - 60 MPH (ft/sec.^2)	9	9	9	9	7	7	9	9	10
(m/sec.^2)	3	3	3	3	2	2	3	3	3
30 - 60 MPH (ft./sec.^2)	6	6	6	6	5	5	6	6	7
(m/sec.^2)	2	2	2	2	2	2	2	2	2
50 - 70 MPH (ft./sec.^2)	10	10	10	10	10	10	10	10	12
(m/sec.^2)	3	3	3	3	3	3	3	3	4
Coast Down Measurement									
* 30 MPH (HP)	7	*7*	*7*	*7*	*7*	*7*	*7*	*7*	*7*
* 50 MPH (HP)	17	*17*	*17*	*17*	*18*	*17*	*17*	*17*	*17*
* 70 MPH (HP)	36	*36*	*37*	*36*	*36*	*38*	*37*	*37*	*37*
Range Estimated									
Highway (miles)	598	575	480	500	550	550	432	525	460
City (miles)	391	391	340	360	352	352	306	450	288
FCV Conversion									
FCV Chassis (no power train) (lbs.)	2922	2925	2933	2655	3255	3445	3038	3108	2674
* Electric Drive System Weight (lbs.)									
* Battery Weight (lbs.)									
* Fuel Cell Weight (lbs.)									
FCV Curb Weight (lbs.)	2922	2925	2933	2655	3255	3445	3038	3108	2674
Sales Data		(1991 cy)				(1991 cy)			
* Number of Units Sold in 1991	103139	35103	16900	64349	11460	3900	11801	22017	73318
* Retail Price	17300	21865	31211	19563	18700	23040	19563	31740	36360

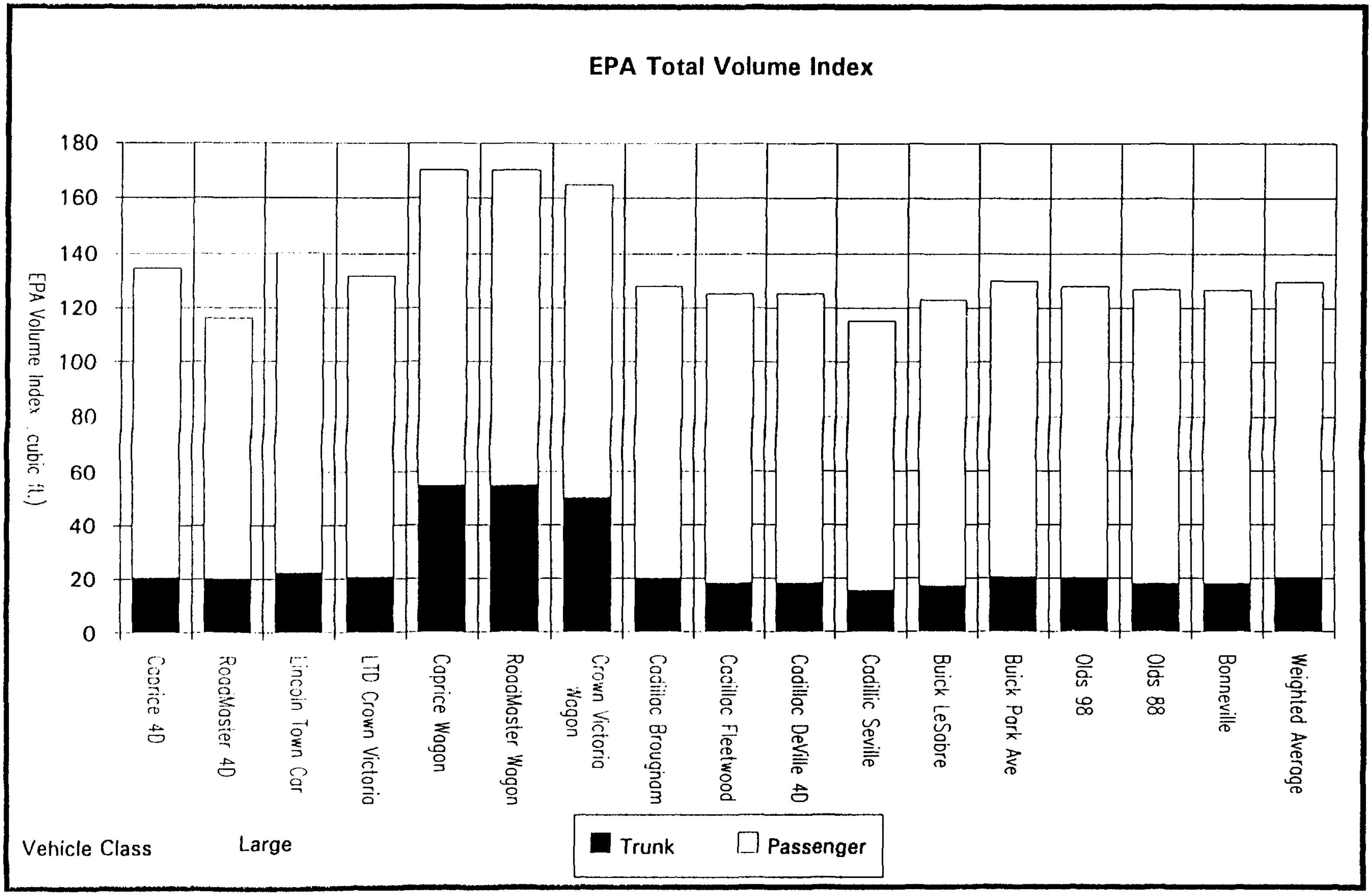
Vehicle Identification								
Vehicle #	10	11	12	13	14	15	16	**************
Year	1992	1992	1992	1992	1991	1992	1992	
Manufacture	Cadillac	Cadillac	Buick	Buick	Olds	Olds	Pontiac	**Large Car**
Model	DeVille 4D	Seville	LeSabre	ParkAve.	98	88	Bonnie.	**Weighted**
Vehicle Class	Large	Large	Large	Large	Large	Large	Large	**Average**
Design Specification								
* Curb Weight (lbs.)	3424	3550	3279	3580	3593	3404	3351	**3631**
* GVM (lbs.)								
* Weight Distribution (% Front)	*63*	*63*	*64*	*63*	63	64	64	**59**
* Wheel Base (in)	111	108	111	111	111	111	111	**113**
* Overall Length (in)	205	202	197	205	206	200	200	**208**
* Overall Width (in)	73	76	72	75	75	74	75	**75**
* Frontial Area (Ft^2)	*25.0*	*25.0*	*23.0*	*23.0*	*23.0*	*23.0*	*23.0*	**24.5**
* Drag Coefficient	*0.34*	*0.34*	*0.32*	*0.32*	*0.32*	*0.32*	*0.32*	**0.34**
Shadow Area (Ft^2)	106	106	99	107	106	*103*	*103*	**109**
* Engine Size (liters)	4.9	4.9	3.8	3.8	3.8	3.8	3.8	
* Net Horsepower (HP)	200	200	165	170	170	170	170	**179**
* Torque (Ft.-lbs.)	275	275	210	220	220	220	220	
* Number of Passengers	6	5	6	6	6	6	6	**6**
* Fuel Tank Size (gal.)	18	19	18	18	18	18	18	
* Oil Capacity (qt.)	5	5	4	4	5	5	5	
* Coolant (Water) Capacity (qt.)	12	11	12	*17*	12	12	12	
Tire Size								
* Width (mm)	*205*	*205*	*215*	215	215	225	225	
* Aspect Ratio	*70*	*70*	*65*	65	60	60	60	
* Rim (in.)	15	16	15	15	15	15	15	
Component Weight Estimates								
* Engine Dressed-Measured (lbs.)								
Engine Dressed-Estimated (lbs.)	613	613	475	475	475	475	475	
* Transmission & Convertor-Measured (lbs.)								
Transmission & Convertor-Estimated (lbs.)	186	186	144	144	144	144	144	
Fuel & Tank Weight-Estimated (lbs.)	132	138	132	132	132	132	132	
Coolant Weight (lbs.)	9	9	8	8	8	8	9	
Cooling System Components Wgt.-Est. (lbs.)	28	25	27	40	28	28	28	
Cooling System Components Wgt.-Est. (lbs.)								
Powertrain Weight-Estimated (lbs.)	968	971	786	798	787	787	788	**902**
EPA								
* EPA Volume Index (Ft.^3)	125.3	115.1	123	130	128	127	126.8	**129.8**
* Trunk Volume (Ft.^3)	18.1	15.3	17	20.3	20	18	18	**20.2**
Passenger Volume (Ft.^3)	107.2	99.8	106	109.7	108	109	108.8	**109.6**
* EPA Highway Mileage (MPG)	25	25	28	27	27	28	27	**25.7**
* EPA City Mileage (MPG)	16	16	18	18	18	18	18	**17.1**
Performance								
* 0 - 60 MPH (96.6 KPH)(sec.)	8.5	8.8	10.1	9.7	9.2	8.8	8.7	**9.5**
* 30 - 50 MPH (sec.)	*4*	*4*	*5*	4.6	4.4	4.2	4.1	**4.7**
* 50 - 70 MPH (sec.)	*6*	*6*	*7.3*	6.8	6.3	6	6	**6.7**
* 1/4 Mile Elapsed Time (sec.)	16.5	16.7	*17.4*	17.1	16.9	16.8	16.9	**17.0**
* Top Speed (MPH)	112	*112*	112	106	107	107	108	**108.3**
Average Accelerations								
0 - 60 MPH (ft/sec.^2)	10	10	9	9	10	10	10	
(m/sec.^2)	3	3	3	3	3	3	3	
30 - 50 MPH (ft./sec.^2)	7	7	6	6	7	7	7	
(m/sec.^2)	2	2	2	2	2	2	2	
50 - 70 MPH (ft./sec.^2)	12	12	10	11	12	12	12	
(m/sec.^2)	4	4	3	3	4	4	4	
Coast Down Measurement								
* 30 MPH (HP)	*7*	*7*	7	6	6	6	*6*	
* 50 MPH (HP)	*17*	*17*	17	16	15	15	*15*	
* 70 MPH (HP)	*37*	*37*	37	35	33	32	*32*	
Range Estimated								
Highway (miles)	450	470	504	486	486	504	486	**503**
City (miles)	288	301	324	324	324	324	324	**324**
FCV Conversion								
FCV Chassis (no power train) (lbs.)	2456	2679	2493	2782	2806	2617	2563	**2729**
Electric Drive System Weight (lbs.)								
Battery Weight (lbs.)								
Fuel Cell Weight (lbs.)								
FCV Curb Weight (lbs.)	2456	2679	2493	2782	2806	2617	2563	**2729**
Sales Data								**# sold - total**
* Number of Units Sold in 1991	73318	26688	112207	83831	59828	81325	72625	**961809**
* Retail Price	*31740*	*34975*	*18695*	*26285*	*24595*	*18495*	18599	**24336**
								weighted avg.

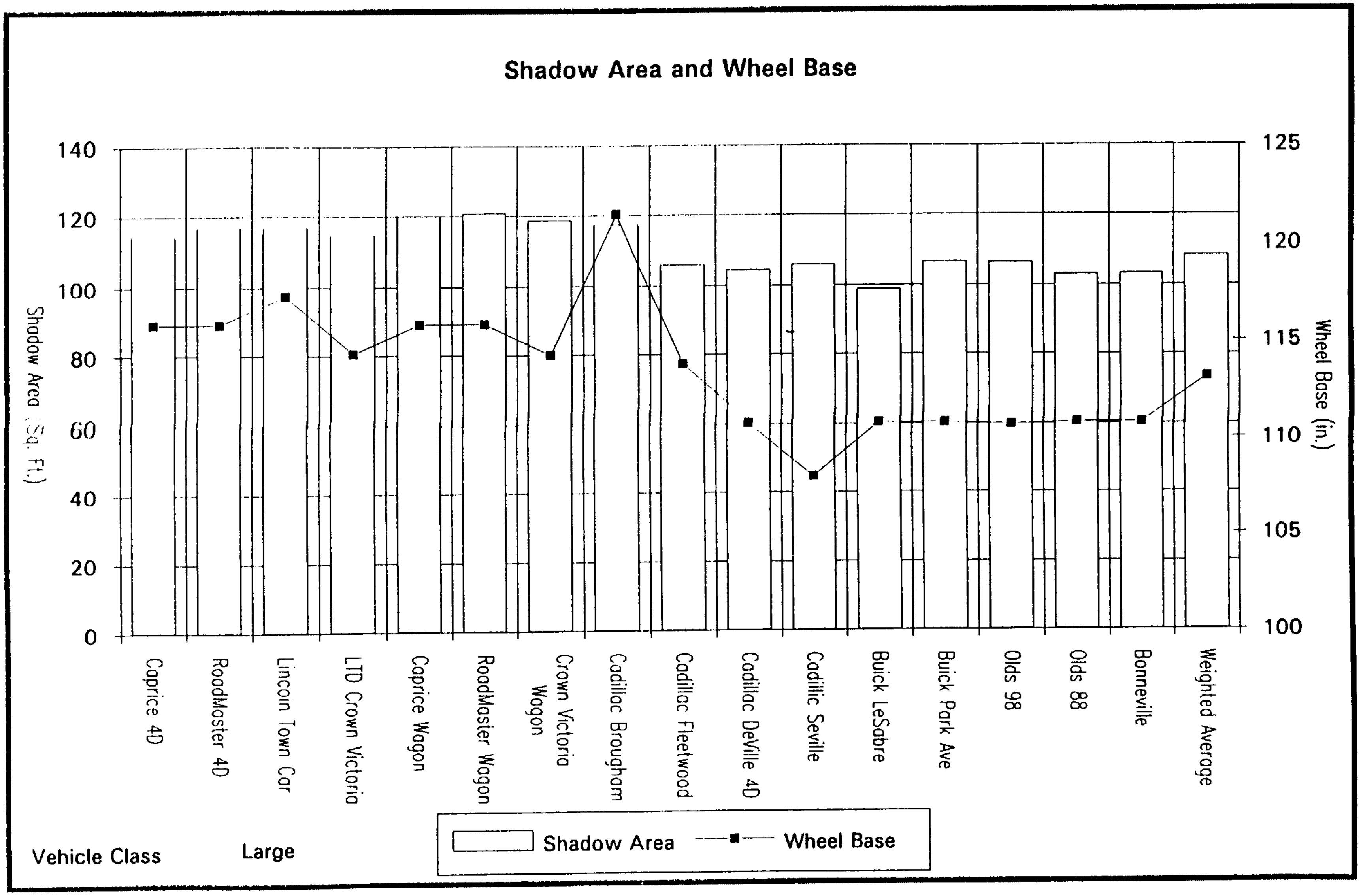
Vehicle Identification									
Vehicle #	17	18	19	20	21	22	23	24	**********
Year	1991	1991	1991	1991	1991	1991	1991	1991	
Manufacture	Chevy	Pontiac	Ford	Dodge	Toyota	Mazda	GMC	GMC	MiniVan
Model	Lum APV	Transport	Aerostar	Caravan	Privia	MPV	Safari	Safari	Weighted
Vehicle Class	MiniVan	MiniVan	MiniVan	MiniVan	MiniVan	MiniVan	Pass.	Cargo	Average
Design Specification									
* Curb Weight (lbs.)	3295	3677	*3700*	3701	3585	3650	3833	3502	3644
* GVM (lbs.)	5126	*4012*	4820		5215		5700	5000	
* Weight Distribution (% Front)	51	*50*	*52*	60	53	*60*	57	58	56
* Wheel Base (in)	110	110	119	112	113	110	111	111	113
* Overall Length (in)	194	195	175	178	187	176	177	177	180
* Overall Width (in)	74	76	*72*	72	71	72	77	78	72
* Frontial Area (Ft^2)	29.3	29.3	*30.0*	*30.0*	*30.0*	*27.0*	*31.0*	*31.0*	29.7
* Drag Coefficient	0.33	0.33	*0.35*	*0.35*	*0.34*	*0.34*	0.37	0.37	0.36
Shadow Area (Ft^2)	100	101	87	89	92	88	95	95	91
* Engine Size (liters)	3.1	3.1	3	3.3	2.4	2.6	4.3	*4.3*	
* Net Horsepower (HP)	120	120	145	100	138	121	150	*150*	123
* Torque (Ft.-lbs.)	170	175	130	185	154	121	230	*230*	
* Number of Passengers	7	6	7	7	7	7	8	2	7
* Fuel Tank Size (gal.)	20	20	21	20	20	16	27	27	
* Oil Capacity (qt.)	5	4	68	5	6	*5*	4	*4*	
* Coolant (Water) Capacity (qt.)	12	12	13	10	12	*13*	3	*3*	
Tire Size									
* Width (mm)	205	*205*	*205*	205	215	*205*	205	*205*	
* Aspect Ratio	70	*70*	*70*	70	65	*70*	75	*75*	
* Rim (in.)	15	*14*	14	14	14	14	15	*15*	
Component Weight Estimates									
* Engine Dressed-Measured (lbs.)									
Engine Dressed-Estimated (lbs.)	388	388	376	413	300	325	489	489	
* Transmission & Convertor-Measured (lbs.)									
Transmission & Convertor-Estimated (lbs.)	118	118	114	126	91	99	199	199	
Fuel & Tank Weight-Estimated (lbs.)	147	147	164	147	146	117	198	198	
Oil Weight (lbs.)	9	8	109	8	11	9	8	8	
Coolant Weight (lbs.)	27	29	31	22	29	31	8	8	
Cooling System Components Wgt.-Est. (lbs.)									
Powertrain Weight-Estimated (lbs.)	689	689	783	716	576	581	901	901	719
EPA									
* EPA Volume Index (Ft.^3)	*164.9*	*164.9*	*140*	148	184	*100*	*181.5*	181.5	149.7
* Trunk Volume (Ft.^3)	18.4	*18.4*	*20*	10	28	*18*	*85.8*	86.8	21.5
Passenger Volume (Ft.^3)	146.5	*94.2*	*120*	138	156	*82*	*95.7*	95.7	126.1
* EPA Highway Mileage (MPG)	23	23	22	23	20	*23*	21	*21*	22
* EPA City Mileage (MPG)	18	18	17	18	17	*17*	16	*16*	17.125
Performance									
* 0 - 60 MPH (96.6 KPH)(sec.)	12.2	13.2	*11*	10.8	12.2	11	12.6	12.6	11.3
* 30 - 50 MPH (sec.)	*5.7*	*5.7*	*5.7*	5.7	5.7	*5.7*	*5.7*	*5.7*	5.7
* 50 - 70 MPH (sec.)	*9.2*	*9.2*	*7*	8.1	9.2	*8*	*6*	*6*	7.9
* 1/4 Mile Elapsed Time (sec.)	18.7	19.1	*18*	18.1	19	18	18.9	18.9	18.3
* Top Speed (MPH)	105	105	*105*	107	104	*100*	*105*	*105*	105.2
Average Accelerations									
0 - 60 MPH (ft/sec.^2)	7	7	8	8	7	8	7	7	
(m/sec.^2)	2	2	2	2	2	2	2	2	
30 - 50 MPH (ft./sec.^2)	5	5	5	5	5	5	5	5	
(m/sec.^2)	2	2	2	2	2	2	2	2	
50 - 70 MPH (ft./sec.^2)	8	8	10	9	8	9	12	12	
(m/sec.^2)	2	2	3	3	2	3	4	4	
Coast Down Measurement									
* 30 MPH (HP)	*6*	*6*	*7*	6	6	*6*	*7.5*	*7.5*	
* 50 MPH (HP)	*17*	*17*	*18*	17	17	*17*	*18*	*18*	
* 70 MPH (HP)	*37*	*37*	*37*	38	38	*37*	*38*	*38*	
Range Estimated									
Highway (miles)	460	460	462	460	396	366	567	567	464
City (miles)	360	360	357	360	337	270	432	432	363
FCV Conversion									
FCV Chassis (no power train) (lbs.)	2606	2888	2917	2986	3009	3069	2932	2601	2925
* Electric Drive System Weight (lbs.)									
* Battery Weight (lbs.)									
* Fuel Cell Weight (lbs.)									
FCV Curb Weight (lbs.)	2606	2888	2917	2986	3009	3069	2932	2601	2925
Sales Data									# sold - total
* Number of Units Sold in 1991	48117	23682	147373	207919	52099	48144	20673	20673	568680
* Retail Price	15570	16225	15739	13601	17518	16290	15404	14063	15063
									weighted avg.

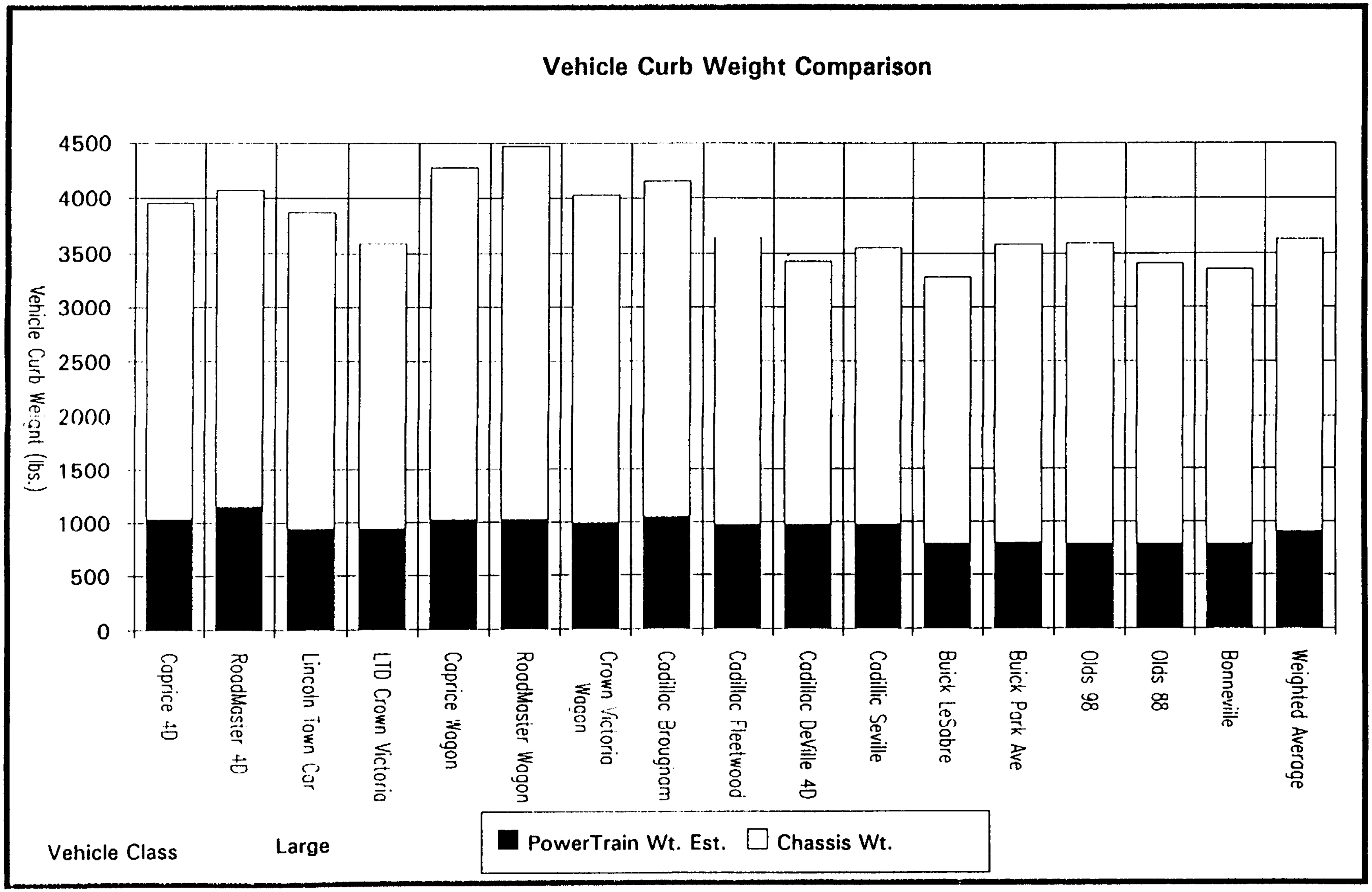
Vehicle Identification								
Vehicle #	25	26	27	28	29	30	31	**********
Year	1991	1991	1991	1991	1991	1992	1992	
Manufacture	Buick	Old	Pontiac	Mercury	Ford	Mercrury	Honda	Midsize
Model	Regal	Cutlass Sp	Grd Prix	Sable	Taurus	Tracer	Accord	Weighted
Vehicle Class	Med	Med 4D	Med	Med	Med	Med	Med 4D	Average
Design Specification								
* Curb Weight (lbs.)	3385	3376	3219	3027	2891	2366	2733	2988
* GVM (lbs.)								
* Weight Distribution (% Front)	65	63	66	64	64	60	62	63
* Wheel Base (in)	108	108	108	106	106	98	107	107
* Overall Length (in)	196	194	195	192	192	171	185	190
* Overall Width (in)	73	71	72	71	71	67	67	70
* Frontial Area (Ft^2)	21.3	21.3	21.3	21.3	21.3	20.0	21.0	21.2
* Drag Coefficient	0.35	0.35	0.35	0.34	0.34	0.35	0.35	0.35
Shadow Area (Ft^2)	96	96	97	95	95	79	86	92
* Engine Size (liters)	3.8	3.1	3.1	3	3	1.9	2.2	
* Net Horsepower (HP)	170	140	140	135	135	88	125	135
* Torque (Ft.-lbs.)	220	185	185	167	165	108	137	
* Number of Passengers	6	6	6	6	6	5	5	6
* Fuel Tank Size (gal.)	17	17	17	16	16	12	17	
* Oil Capacity (qt.)	5	6	4	4	5	4	6	
* Coolant (Water) Capacity (qt.)	13	12	12	10	12	6	7	
Tire Size								
* Width (mm)	225	225	225	205	205	195	195	
* Aspect Ratio	60	60	60	65	65	70	65	
* Rim (in.)	14	15	15	15	14	13	14	
Component Weight Estimates								
* Engine Dressed-Measured (lbs.)								
Engine Dressed-Estimated (lbs.)	476	388	388	376	376	238	276	
* Transmission & Convertor-Measured (lbs.)								
Transmission & Convertor-Estimated (lbs.)	144	118	118	114	114	72	84	
Fuel & Tank Weight-Estimated (lbs.)	121	121	121	117	117	87	125	
Oil Weight (lbs.)	9	8	8	8	8	8	10	
Coolant Weight (lbs.)	31	28	29	23	27	12	17	
Cooling System Components Wgt.-Est. (lbs.)								
Powertrain Weight-Estimated (lbs.)	781	663	663	637	642	417	510	611
EPA								
* EPA Volume Index (Ft.^3)	116.5	116	110.4	116.9	117.9	102	100	110.8
* Trunk Volume (Ft.^3)	15.8	16	14.9	17.2	17.9	13.2	16	16.4
Passenger Volume (Ft.^3)	100.7	100	95.5	99.7	100	88.8	84	94.3
* EPA Highway Mileage (MPG)	28	29	29	28	28	31	28	28.7
* EPA City Mileage (MPG)	19	19	21	20	20	24	23	20.9
Performance								
* 0 - 60 MPH (96.6 KPH)(sec.)	9.2	7.8	7.4	9.2	9.7	11	9	9.0
* 30 - 50 MPH (sec.)	4.6	4	3	4.5	4.5	4	4	4.2
* 50 - 70 MPH (sec.)	6.4	4.4	4.4	6.7	6.7	5	5	5.7
* 1/4 Mile Elapsed Time (sec.)	16.9	16	15.8	17	17.3	17	17	16.9
* Top Speed (MPH)	110	118	129	116	108	105	115	113.9
Average Accelerations								
0 - 60 MPH (ft/sec.^2)	10	11	12	10	9	8	10	
(m/sec.^2)	3	3	4	3	3	2	3	
30 - 50 MPH (ft./sec.^2)	6	7	10	7	7	7	7	
(m/sec.^2)	2	2	3	2	2	2	2	
50 - 70 MPH (ft./sec.^2)	11	17	17	11	11	15	15	
(m/sec.^2)	3	5	5	3	3	4	4	
Coast Down Measurement								
* 30 MPH (HP)	5	5	6	6	6	6	5	
* 50 MPH (HP)	13	13	15	14	14	15	11	
* 70 MPH (HP)	29	29	30	30	30	24	26	
Range Estimated								
Highway (miles)	462	479	479	448	448	369	476	461
City (miles)	314	314	347	320	320	286	391	327
FCV Conversion								
FCV Chassis (no power train) (lbs.)	2604	2712	2556	2390	2349	1939	2223	2377
* Electric Drive System Weight (lbs.)								
* Battery Weight (lbs.)								
* Fuel Cell Weight (lbs.)								
FCV Curb Weight (lbs.)	2604	2712	2556	2390	2349	1939	2223	2377
Sales Data								
* Number of Units Sold in 1991	104802	87540	103203	100331	299659	34439	323088	1053062
* Retail Price	16610	16795	16390	16418	14980	9773	11585	14175

Vehicle Identification								
Vehicle #	32	33	34	35	36	37	38	39
Year	1991	1991	1991	1992	1992	1992	1991	1991
Manufacture	Chevy	Pontiac	Ford	Ford	Jeep/Egl	Honda	Nissan	Nissan
Model	Cavalier	Sunbird	Escort	Tempo 2D	Talon	Civic	Sentra	300 zx
Vehicle Class	Comp 4D	Comp 4D	Comp	Comp	Comp	Comp	Comp	Comp
Design Specification								
* Curb Weight (lbs.)	2481	2537	2364	2414	2712	2276	2288	3186
* GVM (lbs.)								
* Weight Distribution (% Front)	61	*61*	67	*61*	60	*62*	*62*	*56*
* Wheel Base (in)	101	101	98	100	97	103	96	97
* Overall Length (in)	182	181	171	177	172	173	170	170
* Overall Width (in)	66	66	67	68	67	67	66	71
* Frontial Area (Ft^2)	*20.2*	*20.2*	*20.0*	*20.0*	*21.0*	21.3	*21.3*	*19.0*
* Drag Coefficient	*0.35*	*0.35*	*0.34*	*0.35*	*0.32*	*0.35*	*0.34*	*0.30*
Shadow Area (Ft^2)	84	83	79	84	80	80	78	83
* Engine Size (liters)	2.2	2	1.9	2.3	2	1.5	1.6	3
* Net Horsepower (HP)	110	110	88	96	135	102	110	222
* Torque (Ft.-lbs.)	130	123	108	128	125	98	108	198
* Number of Passengers	5	5	5	5	4	5	5	2
* Fuel Tank Size (gal.)	14	16	12	16	16	12	13	19
* Oil Capacity (qt.)	4	4	4	4	4	4	6	5
* Coolant (Water) Capacity (qt.)	12	10	5	8	7	5	7	11
Tire Size								
* Width (mm)	*195*	195	185	*195*	*215*	175	*195*	*215*
* Aspect Ratio	60	65	60	*60*	*60*	65	*75*	*60*
* Rim (in.)	14	14	14	14	16	13	13	16
Component Weight Estimates								
* Engine Dressed-Measured (lbs.)								
Engine Dressed-Estimated (lbs.)	275	250	238	288	250	188	200	375
* Transmission & Convertor-Measured (lbs.)								
Transmission & Convertor-Estimated (lbs.)	84	76	72	87	76	57	61	114
Fuel & Tank Weight-Estimated (lbs.)	100	111	87	117	116	87	97	139
Oil Weight (lbs.)	8	7	8	8	8	7	10	9
Coolant Weight (lbs.)	27	23	12	20	16	11	17	25
Cooling System Components Wgt.-Est. (lbs.)								
Powertrain Weight-Estimated (lbs.)	493	468	417	519	466	350	385	663
EPA								
* EPA Volume Index (Ft.^3)	*101.9*	101.9	102	103	*100*	*95*	*103*	*100*
* Trunk Volume (Ft.^3)	*13.6*	13	17	13.2	*15*	*14*	*13.2*	*13*
Passenger Volume (Ft.^3)	*88.3*	88.9	85	89.8	*85*	*81*	*89.8*	*87*
* EPA Highway Mileage (MPG)	36	36	31	26	23	37	37	24
* EPA City Mileage (MPG)	24	26	26	21	19	30	28	18
Performance								
* 0 - 60 MPH (96.6 KPH)(sec.)	9.2	*11*	8.1	*8.8*	6.9	9.4	*11*	*4.5*
* 30 - 50 MPH (sec.)	*4.3*	*4.3*	3.3	*4.3*	*4*	*4*	*4*	*4*
* 50 - 70 MPH (sec.)	*5.5*	*5.5*	5.1	*5.5*	*6*	*6*	*5*	*4*
* 1/4 Mile Elapsed Time (sec.)	16.7	*16.7*	16.4	*16.5*	*169*	17.3	*17*	*14*
* Top Speed (MPH)	*105*	*105*	118	*120*	*120*	111	*104*	*140*
Average Accelerations								
0 - 60 MPH (ft/sec.^2)	10	8	11	10	13	9	8	20
(m/sec.^2)	3	2	3	3	4	3	2	6
30 - 50 MPH (ft./sec.^2)	7	7	9	7	7	7	7	7
(m/sec.^2)	2	2	3	2	2	2	2	2
50 - 70 MPH (ft./sec.^2)	13	13	14	13	12	12	16	18
(m/sec.^2)	4	4	4	4	4	4	4	6
Coast Down Measurement								
* 30 MPH (HP)	*6*	*6*	4	*6*	*5*	*5*	*6*	*5*
* 50 MPH (HP)	*15*	*15*	11	*15*	*13*	*11*	*13*	*11*
* 70 MPH (HP)	*26*	*26*	26	*26*	*29*	*25*	*26*	*23*
Range Estimated								
Highway (miles)	476	547	369	413	363	440	488	466
City (miles)	326	396	309	334	300	357	370	342
FCV Conversion								
FCV Chassis (no power train) (lbs.)	1998	2069	1947	1896	2246	1925	1903	2623
*** Electric Drive System Weight (lbs.)**								
*** Battery Weight (lbs.)**								
*** Fuel Cell Weight (lbs.)**								
FCV Curb Weight (lbs.)	1998	2069	1947	1896	2246	1925	1903	2623
Sales Data								
* Number of Units Sold in 1991	259386	89861	247864	189457	29863	169009	112800	14903
* Retail Price	8999	9720	9796	9987	13862	8100	9900	29706

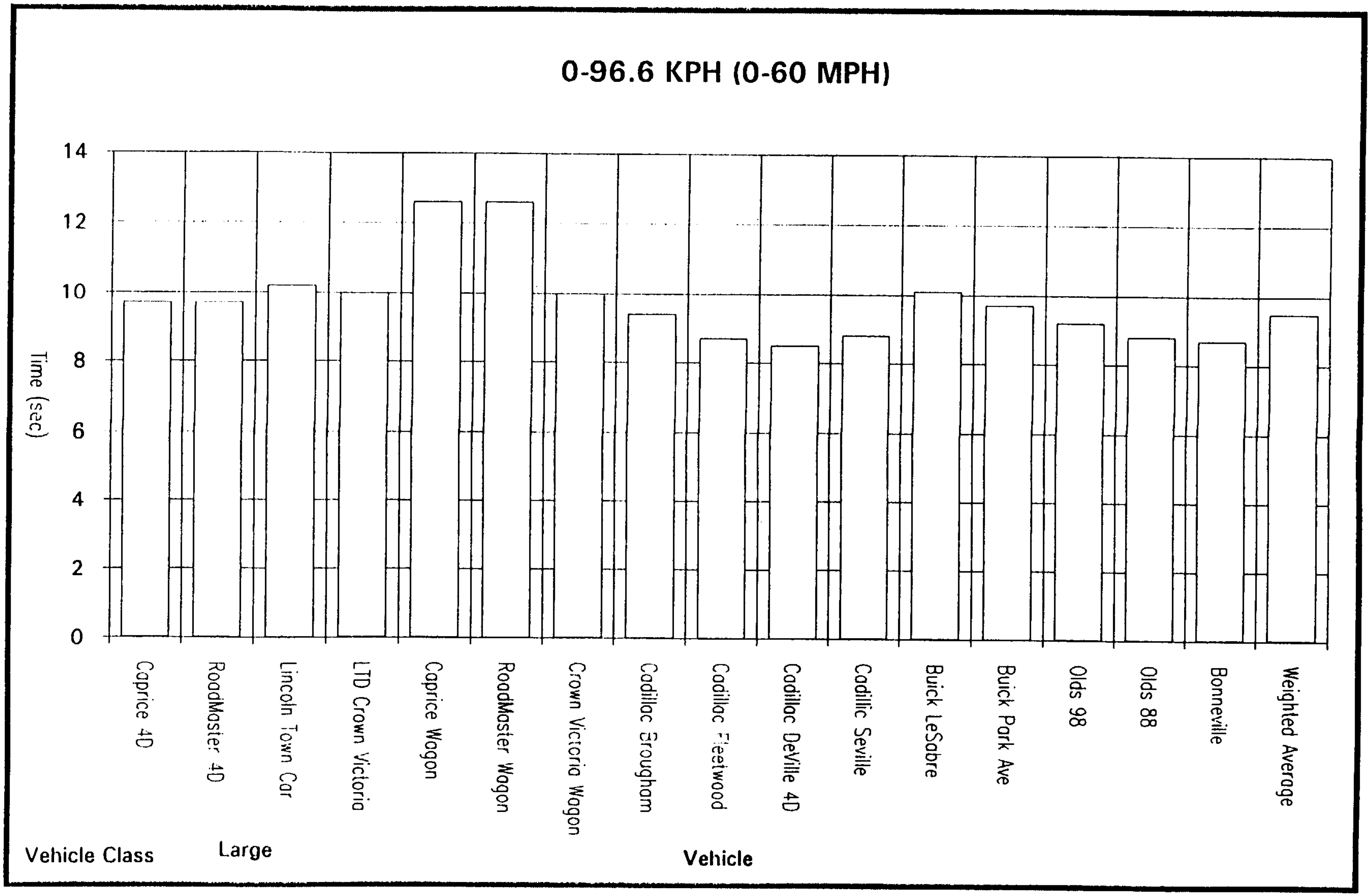
Vehicle Identification			
Vehicle #	40	41	**********
Year	1991	1991	
Manufacture	Mazda	Toyota	Compact
Model	Protege	Tercel	Weighted
Vehicle Class	Comp	Comp	Average
Design Specification			
* Curb Weight (lbs.)	2338	2005	2380
* GVM (lbs.)			
* Weight Distribution (% Front)	62	62	62
* Wheel Base (in)	98	94	99
* Overall Length (in)	172	162	174
* Overall Width (in)	66	65	67
* Frontial Area (Ft^2)	*20.0*	*20.0*	20.3
* Drag Coefficient	*0.36*	*0.35*	0.36
Shadow Area (Ft^2)	78	73	81
* Engine Size (liters)	1.8	1.5	
* Net Horsepower (HP)	103	82	102
* Torque (Ft.-lbs.)	111	89	
* Number of Passengers	5	5	5
* Fuel Tank Size (gal.)	15	12	
* Oil Capacity (qt.)	4	4	
* Coolant (Water) Capacity (qt.)	*7*	6	
Tire Size			
* Width (mm)	185	155	
* Aspect Ratio	60	70	
* Rim (in.)	13	13	
Component Weight Estimates			
* Engine Dressed-Measured (lbs.)			
Engine Dressed-Estimated (lbs.)	225	188	
* Transmission & Convertor-Measured (lbs.)			
Transmission & Convertor-Estimated (lbs.)	68	57	
Fuel & Tank Weight-Estimated (lbs.)	108	87	
Oil Weight (lbs.)	7	7	
Coolant Weight (lbs.)	17	13	
Cooling System Components Wgt.-Est. (lbs.)			
Powertrain Weight-Estimated (lbs.)	424	351	439
EPA			
* EPA Volume Index (Ft.^3)	100	96	100.7
* Trunk Volume (Ft.^3)	13	11	14.0
Passenger Volume (Ft.^3)	87	85	86.7
* EPA Highway Mileage (MPG)	30	35	31.4
* EPA City Mileage (MPG)	25	29	24.6
Performance			
* 0 - 60 MPH (96.6 KPH)(sec.)	8.8	11.2	9.3
* 30 - 50 MPH (sec.)	3.7	4.3	4.0
* 50 - 70 MPH (sec.)	5.7	5.5	5.4
* 1/4 Mile Elapsed Time (sec.)	16.5	18.1	20.4
* Top Speed (MPH)	120	100	111.5
Average Accelerations			
0 - 60 MPH (ft/sec.^2)	10	8	
(m/sec.^2)	3	2	
30 - 50 MPH (ft./sec.^2)	8	7	
(m/sec.^2)	2	2	
50 - 70 MPH (ft./sec.^2)	13	13	
(m/sec.^2)	4	4	
Coast Down Measurement			
* 30 MPH (HP)	4	4	
* 50 MPH (HP)	12	11	
* 70 MPH (HP)	27	26	
Range Estimated			
Highway (miles)	436	417	438
City (miles)	363	345	344
FCV Conversion			
FCV Chassis (no power train) (lbs.)	1914	1654	1940
* Electric Drive System Weight (lbs.)			
* Battery Weight (lbs.)			
* Fuel Cell Weight (lbs.)			
FCV Curb Weight (lbs.)	1914	1654	1940
Sales Data			
* Number of Units Sold in 1991	53474	102043	1258840
* Retail Price	10249	8898	9729

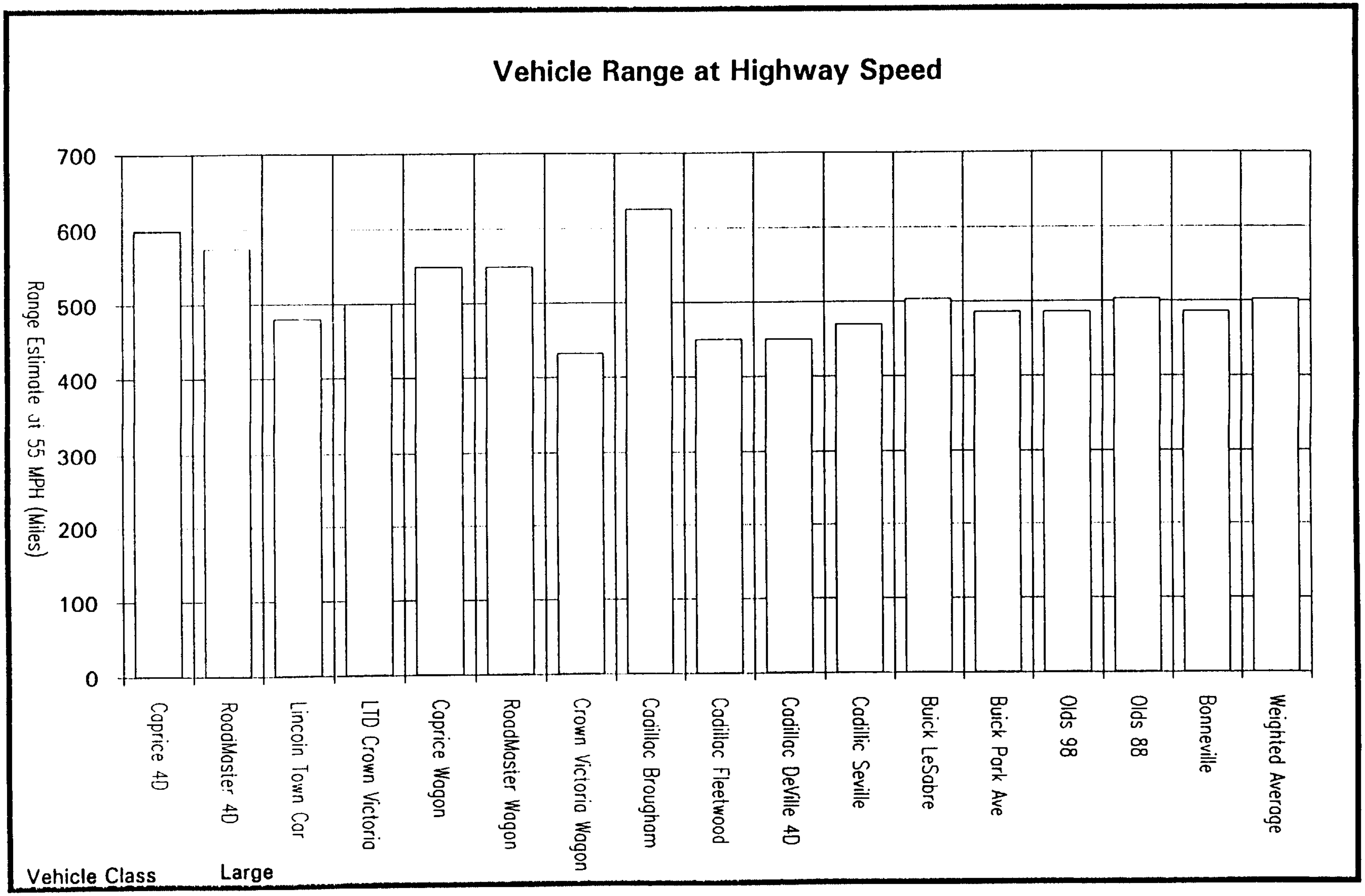

EPA Total Volume Index
180
160
140
120
100
80
60
40
20
0
EPA Volume Index (cubic ft.)
Caprice 4D
RoadMaster 4D
Lincoln Town Car
LTD Crown Victoria
Caprice Wagon
RoadMaster Wagon
Crown Victoria Wagon
Cadillac Brougham
Cadillac Fleetwood
Cadillac DeVille 4D
Cadillic Seville
Buick LeSabre
Buick Park Ave
Olds 98
Olds 88
Bonneville
Weighted Average
Vehicle Class
Large
Trunk
Passenger


Shadow Area and Wheel Base
Shadow Area (Sq. Ft.)
Wheel Base (in.)
140
120
100
80
60
40
20
0
125
120
115
110
105
100
Caprice 4D
RoadMaster 4D
Lincoln Town Car
LTD Crown Victoria
Caprice Wagon
RoadMaster Wagon
Crown Victoria Wagon
Cadillac Brougham
Cadillac Fleetwood
Cadillac DeVille 4D
Cadillic Seville
Buick LeSabre
Buick Park Ave
Olds 98
Olds 88
Bonneville
Weighted Average
Shadow Area
Wheel Base
Vehicle Class
Large

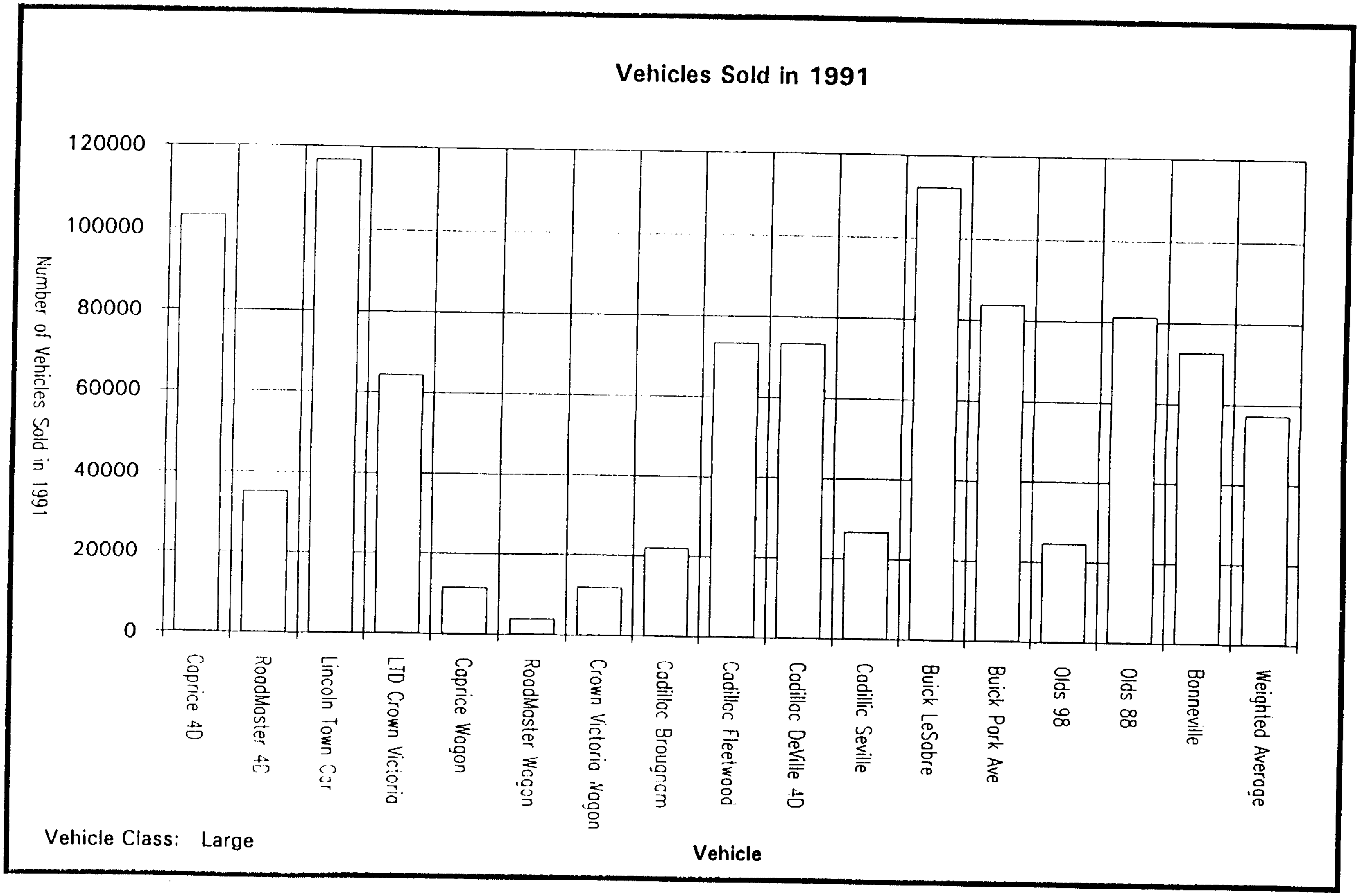


Vehicle Curb Weight Comparison
Vehicle Curb Weight (lbs.)
4500
4000
3500
3000
2500
2000
1500
1000
500
0
Caprice 4D
RoadMaster 4D
Lincoln Town Car
LTD Crown Victoria
Caprice Wagon
RoadMaster Wagon
Crown Victoria Wagon
Cadillac Brougham
Cadillac Fleetwood
Cadillac DeVille 4D
Cadillic Seville
Buick LeSabre
Buick Park Ave
Olds 98
Olds 88
Bonneville
Weighted Average
Vehicle Class
Large
PowerTrain Wt. Est.
Chassis Wt.

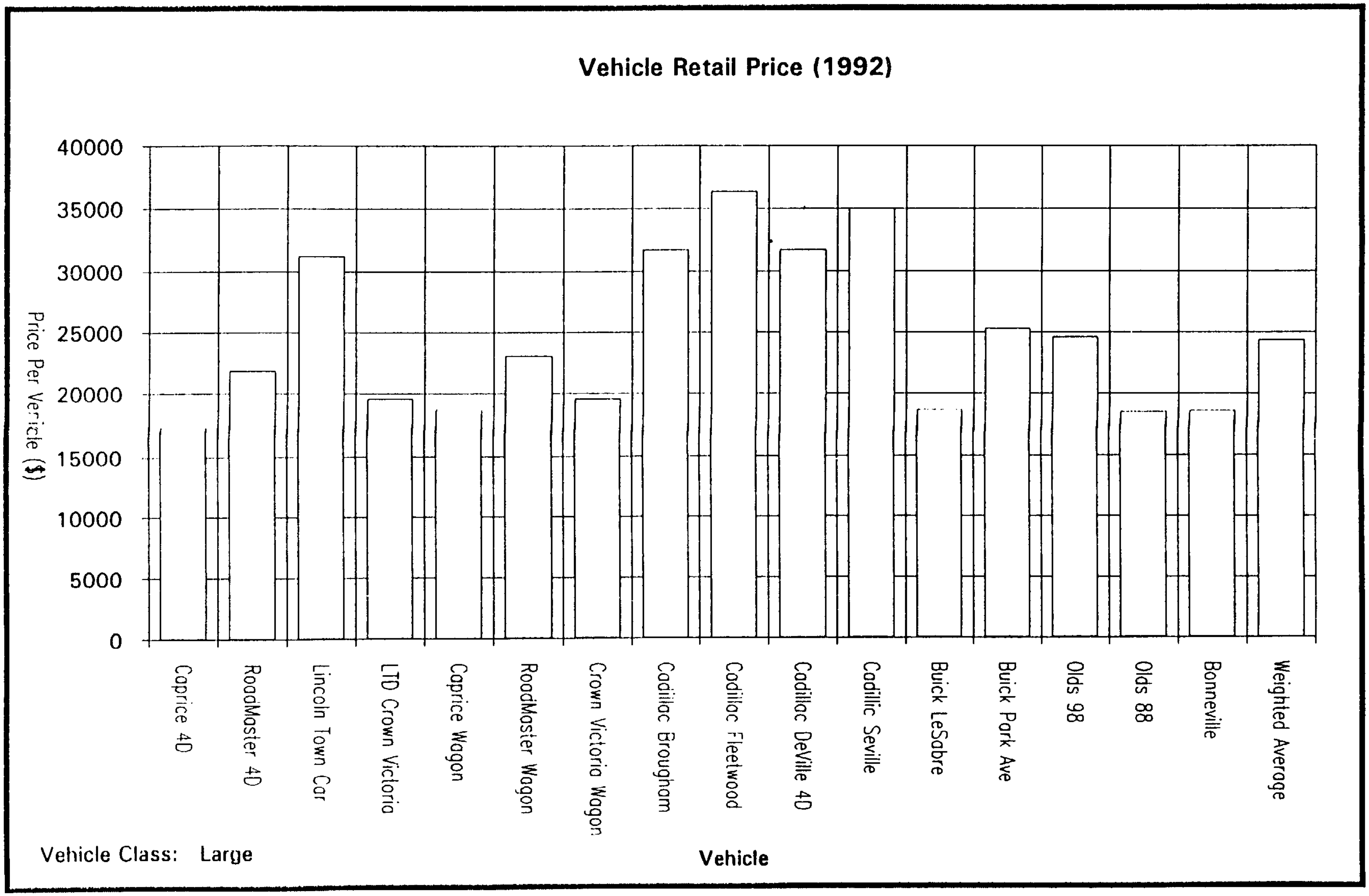

0-96.6 KPH (0-60 MPH)
Time (sec)
14
12
10
8
6
4
2
0
Caprice 4D
RoadMaster 4D
Lincoln Town Car
LTD Crown Victoria
Caprice Wagon
RoadMaster Wagon
Crown Victoria Wagon
Cadillac Brougham
Cadillac Fleetwood
Cadillac DeVille 4D
Cadillic Seville
Buick LeSabre
Buick Park Ave
Olds 98
Olds 88
Bonneville
Weighted Average
Vehicle Class
Large
Vehicle



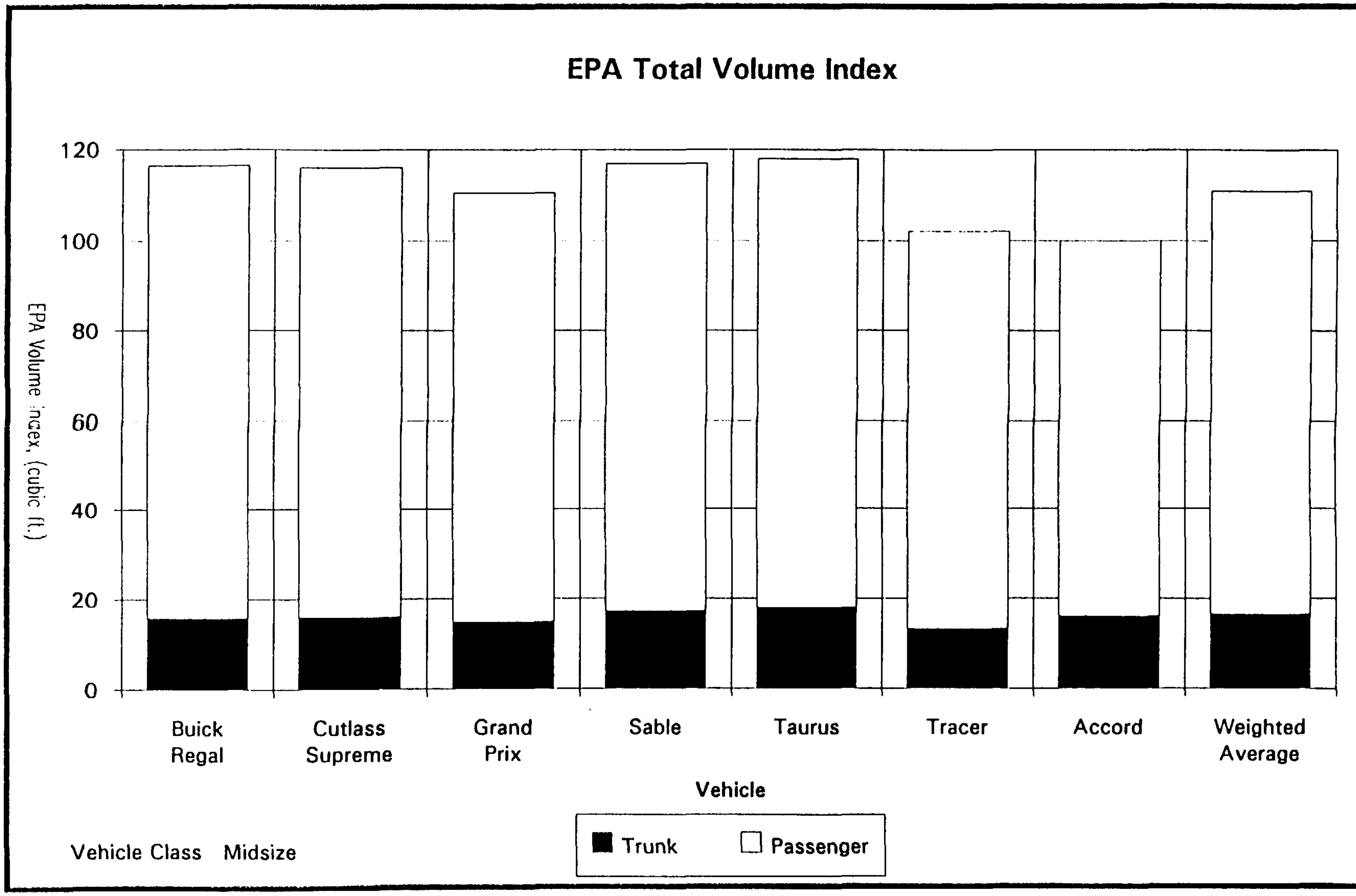
Vehicle Range at Highway Speed
Range Estimate at 55 MPH (Miles)
700
600
500
400
300
200
100
0
Caprice 4D
RoadMaster 4D
Lincoln Town Car
LTD Crown Victoria
Caprice Wagon
RoadMaster Wagon
Crown Victoria Wagon
Cadillac Brougham
Cadillac Fleetwood
Cadillac DeVille 4D
Cadillic Seville
Buick LeSabre
Buick Park Ave
Olds 98
Olds 88
Bonneville
Weighted Average
Vehicle Class
Large

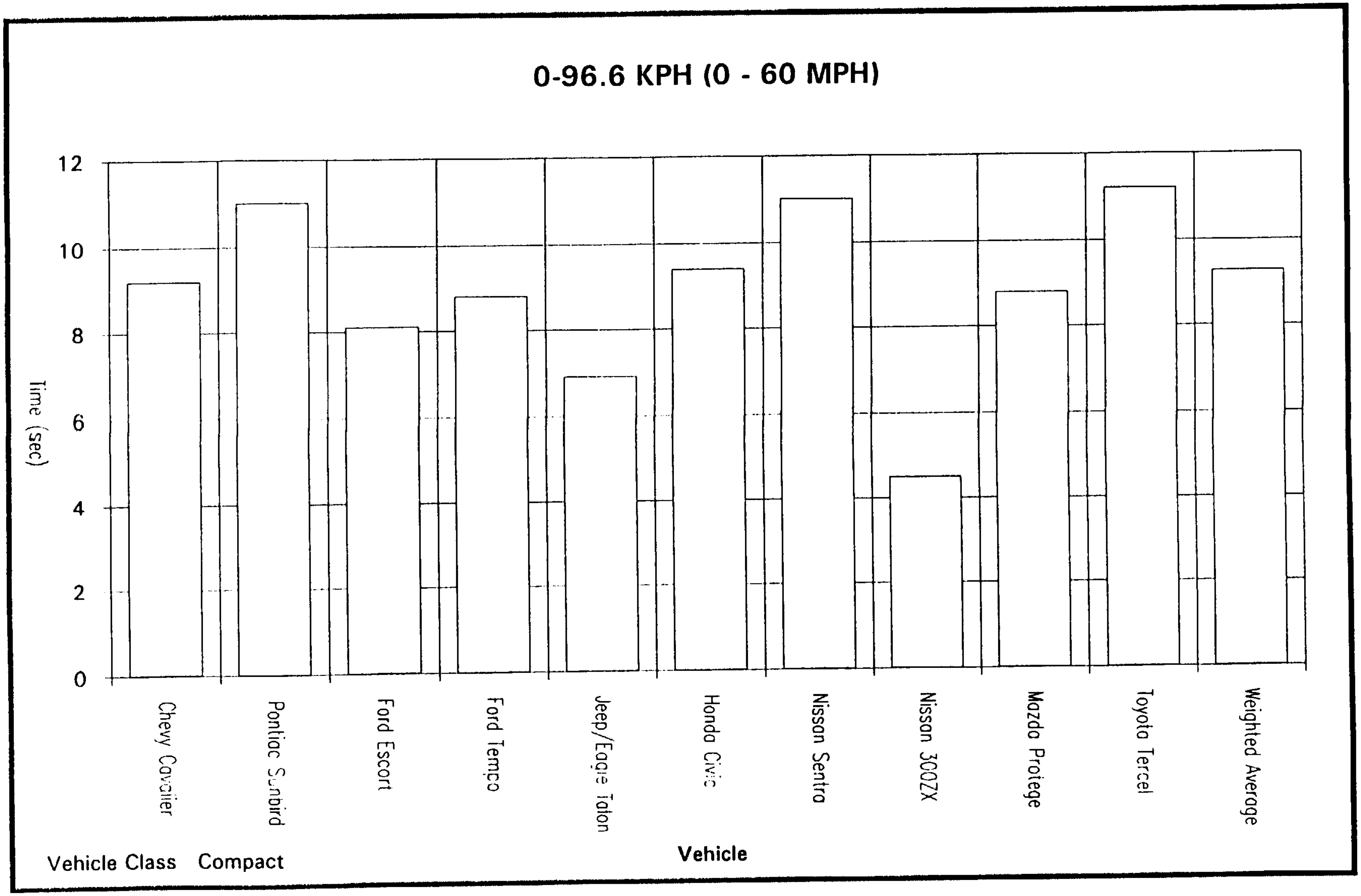


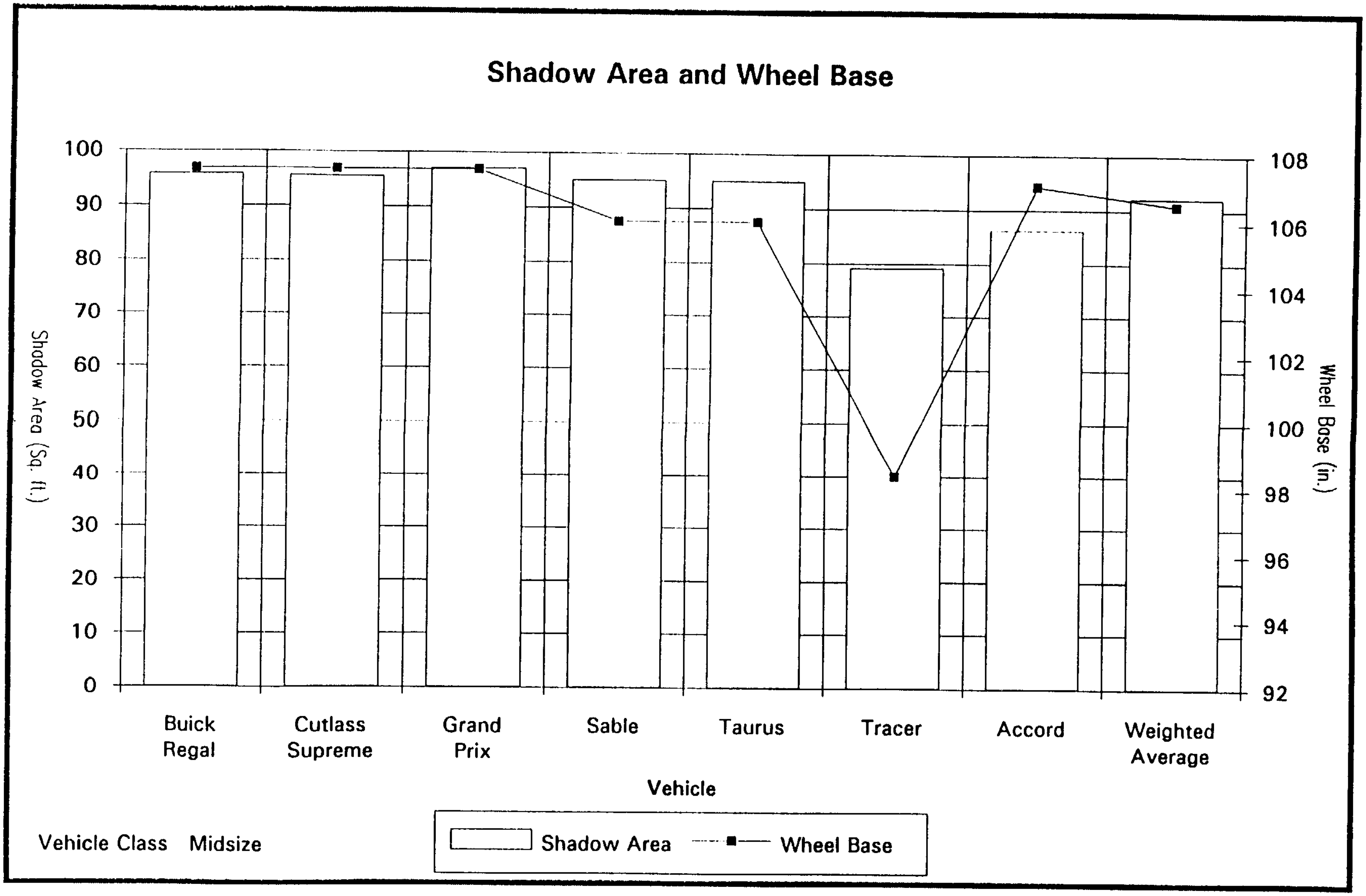
Vehicles Sold in 1991
Number of Vehicles Sold in 1991
120000
100000
80000
60000
40000
20000
0
Caprice 4D
RoadMaster 4D
Lincoln Town Car
LTD Crown Victoria
Caprice Wagon
RoadMaster Wagon
Crown Victoria Wagon
Cadillac Brougham
Cadillac Fleetwood
Cadillac DeVille 4D
Cadillic Seville
Buick LeSabre
Buick Park Ave
Olds 98
Olds 88
Bonneville
Weighted Average
Vehicle Class: Large
Vehicle

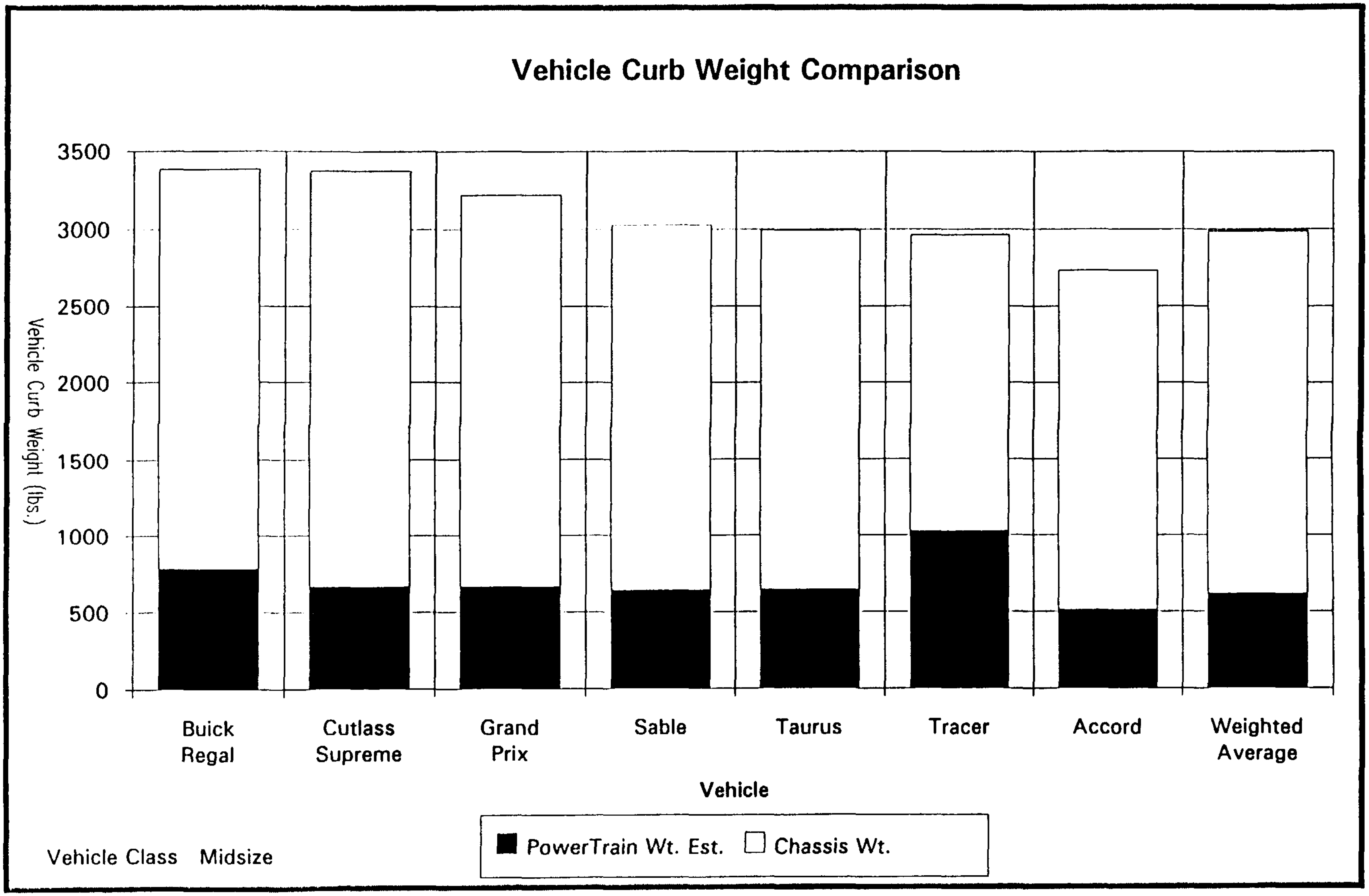


Vehicle Retail Price (1992)
Price Per Vehicle ($)
40000
35000
30000
25000
20000
15000
10000
5000
0
Caprice 4D
RoadMaster 4D
Lincoln Town Car
LTD Crown Victoria
Caprice Wagon
RoadMaster Wagon
Crown Victoria Wagon
Cadillac Brougham
Cadillac Fleetwood
Cadillac DeVille 4D
Cadillic Seville
Buick LeSabre
Buick Park Ave
Olds 98
Olds 88
Bonneville
Weighted Average
Vehicle Class: Large
Vehicle

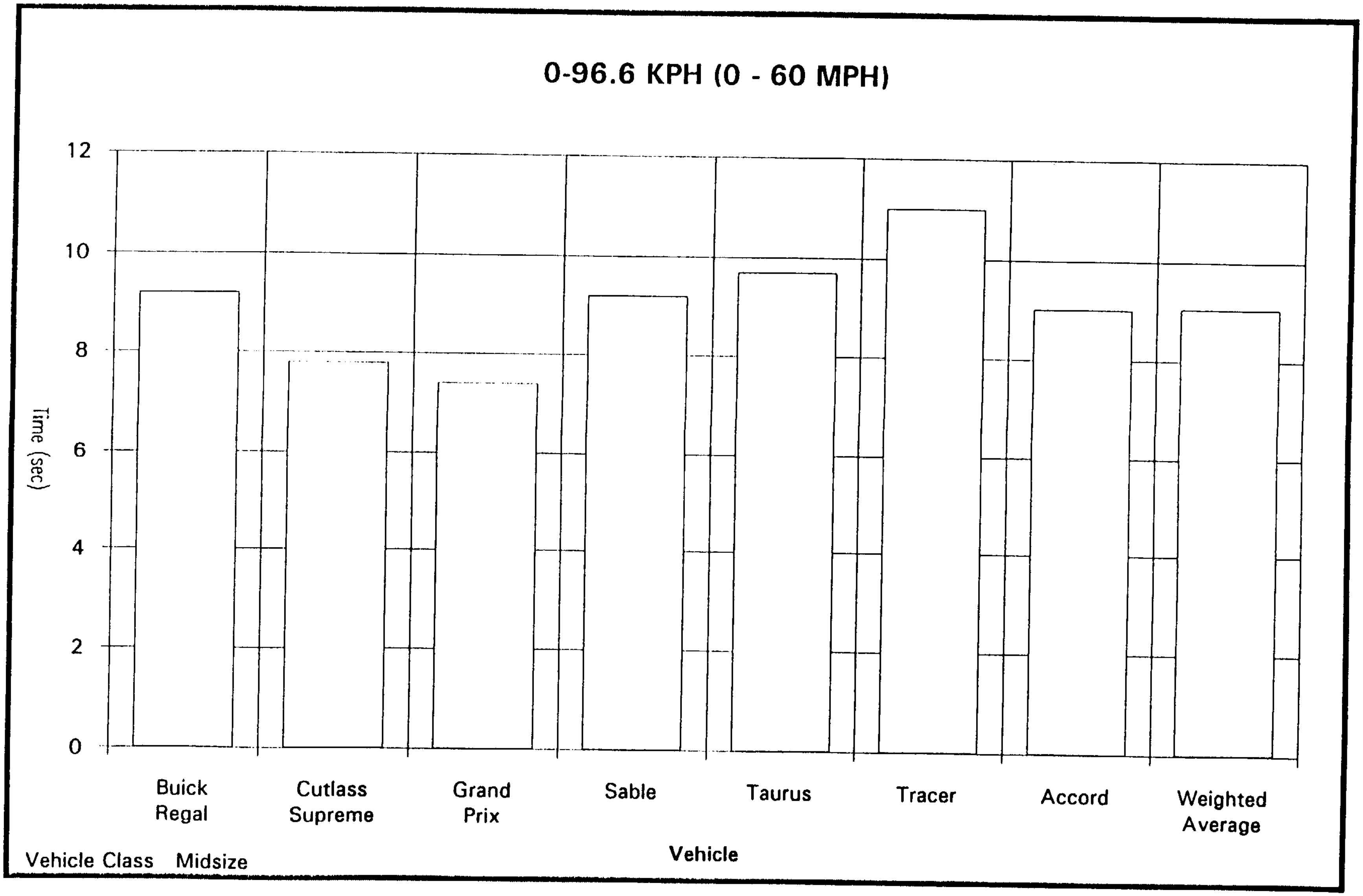

EPA Total Volume Index
120
100
80
60
40
20
0
EPA Volume Index, (cubic ft.)
Buick Regal
Cutlass Supreme
Grand Prix
Sable
Taurus
Tracer
Accord
Weighted Average
Vehicle
Trunk
Passenger
Vehicle Class Midsize

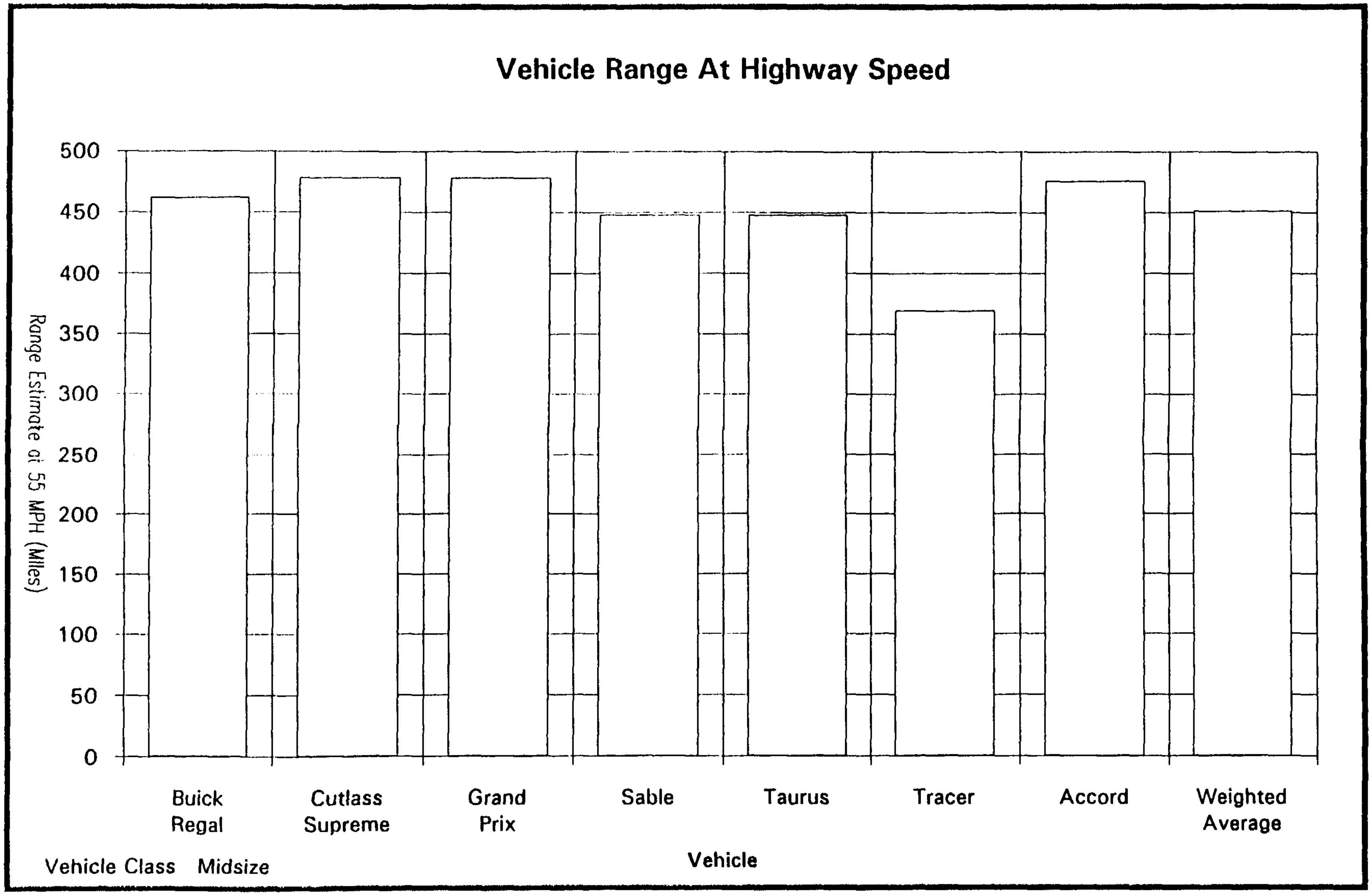

0-96.6 KPH (0 - 60 MPH)
Time (sec)
12
10
8
6
4
2
0
Chevy Cavalier
Pontiac Sunbird
Ford Escort
Ford Tempo
Jeep/Eagle Talon
Honda Civic
Nissan Sentra
Nissan 300ZX
Mazda Protege
Toyota Tercel
Weighted Average
Vehicle
Vehicle Class Compact

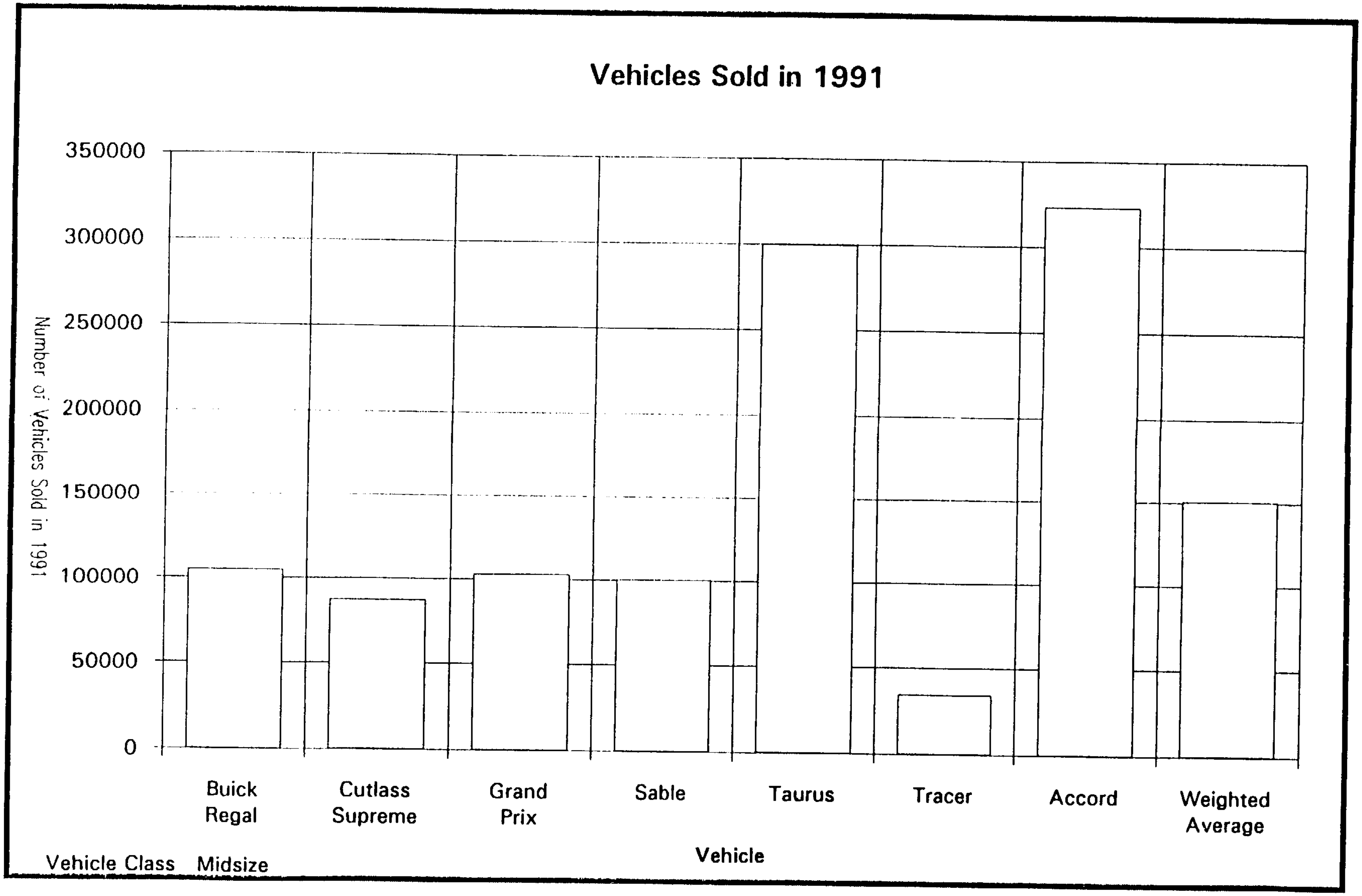

Shadow Area and Wheel Base
100
90
80
70
60
50
40
30
20
10
0
Shadow Area (Sq. ft.)
108
106
104
102
100
98
96
94
92
Wheel Base (in.)
Buick Regal
Cutlass Supreme
Grand Prix
Sable
Taurus
Tracer
Accord
Weighted Average
Vehicle
Vehicle Class Midsize
Shadow Area
Wheel Base

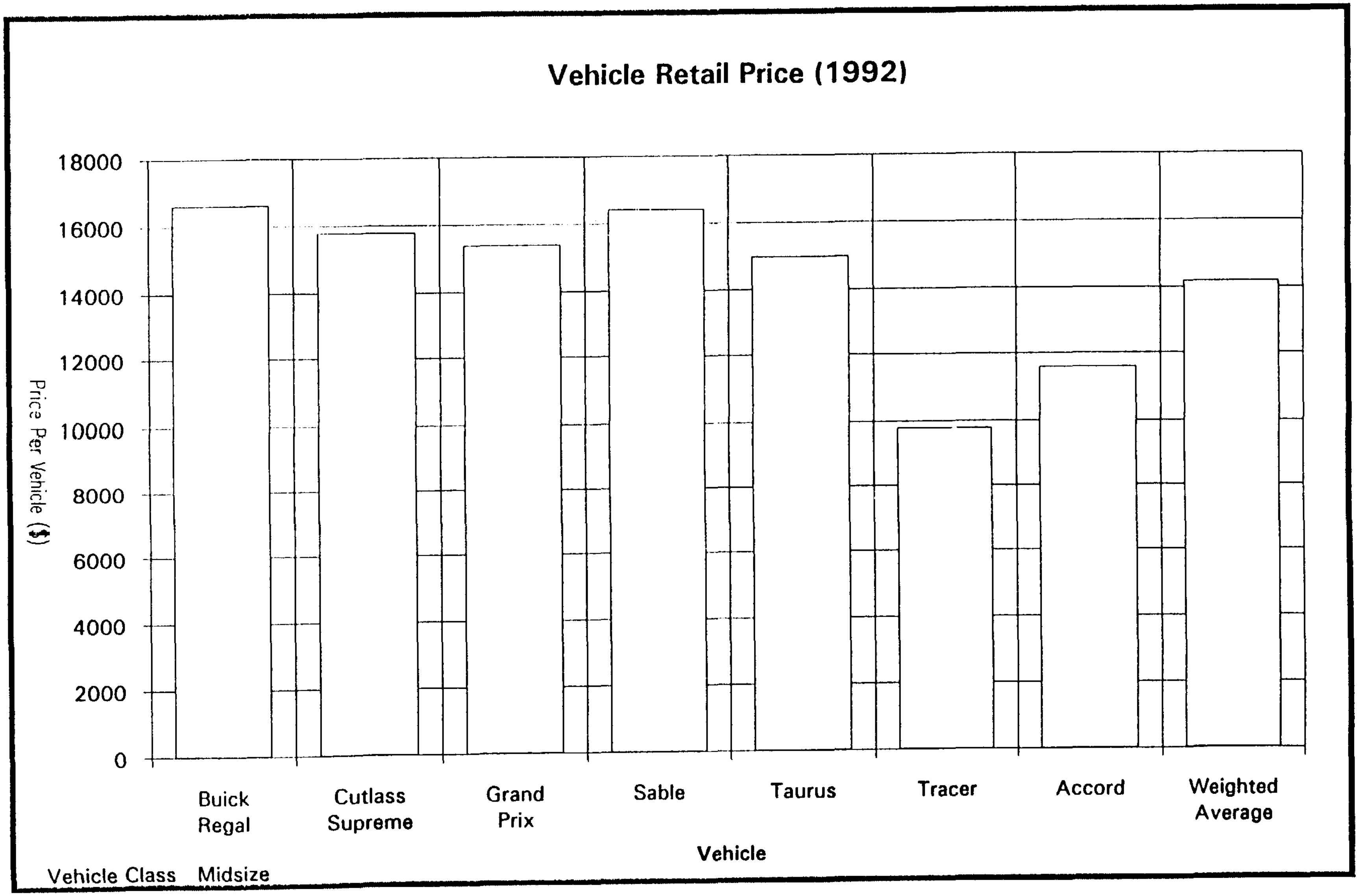


Vehicle Curb Weight Comparison
3500
3000
2500
2000
1500
1000
500
0
Vehicle Curb Weight (lbs.)
Buick Regal
Cutlass Supreme
Grand Prix
Sable
Taurus
Tracer
Accord
Weighted Average
Vehicle
PowerTrain Wt. Est.
Chassis Wt.
Vehicle Class Midsize

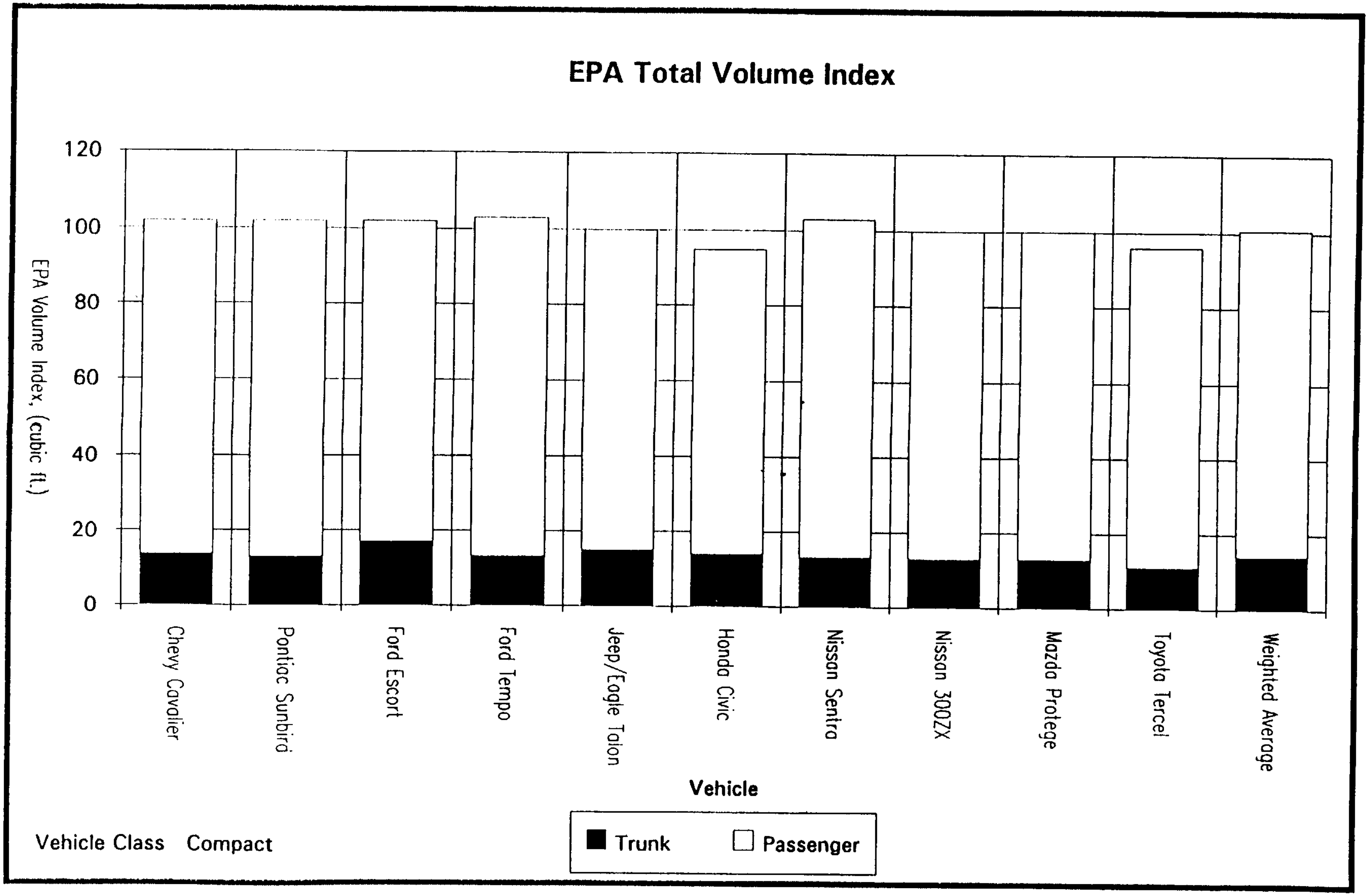

0-96.6 KPH (0 - 60 MPH)
12
10
8
6
4
2
0
Time (sec)
Buick Regal
Cutlass Supreme
Grand Prix
Sable
Taurus
Tracer
Accord
Weighted Average
Vehicle
Vehicle Class Midsize

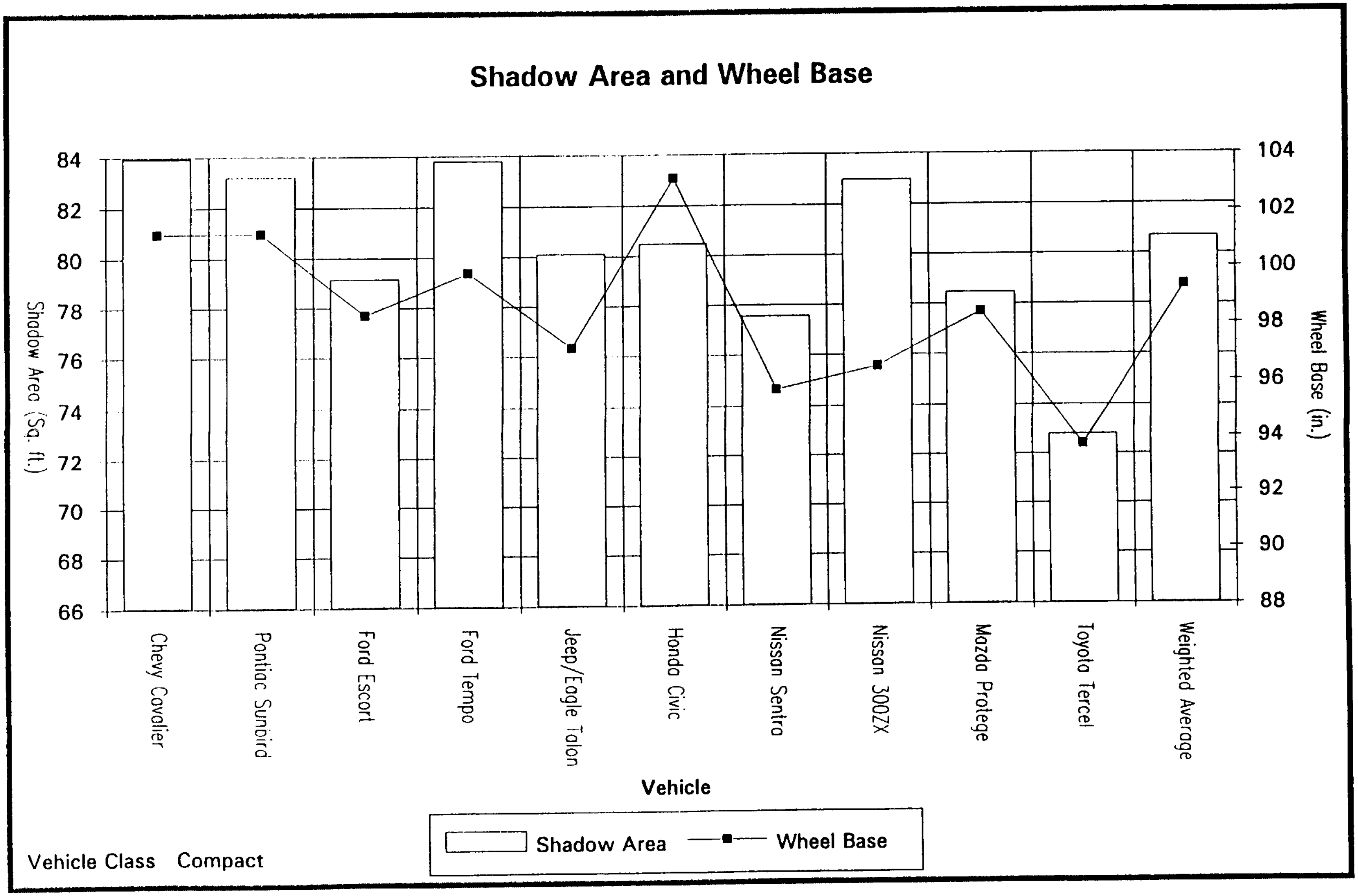

Vehicle Range At Highway Speed
Range Estimate at 55 MPH (Miles)
500
450
400
350
300
250
200
150
100
50
0
Buick Regal
Cutlass Supreme
Grand Prix
Sable
Taurus
Tracer
Accord
Weighted Average
Vehicle
Vehicle Class Midsize

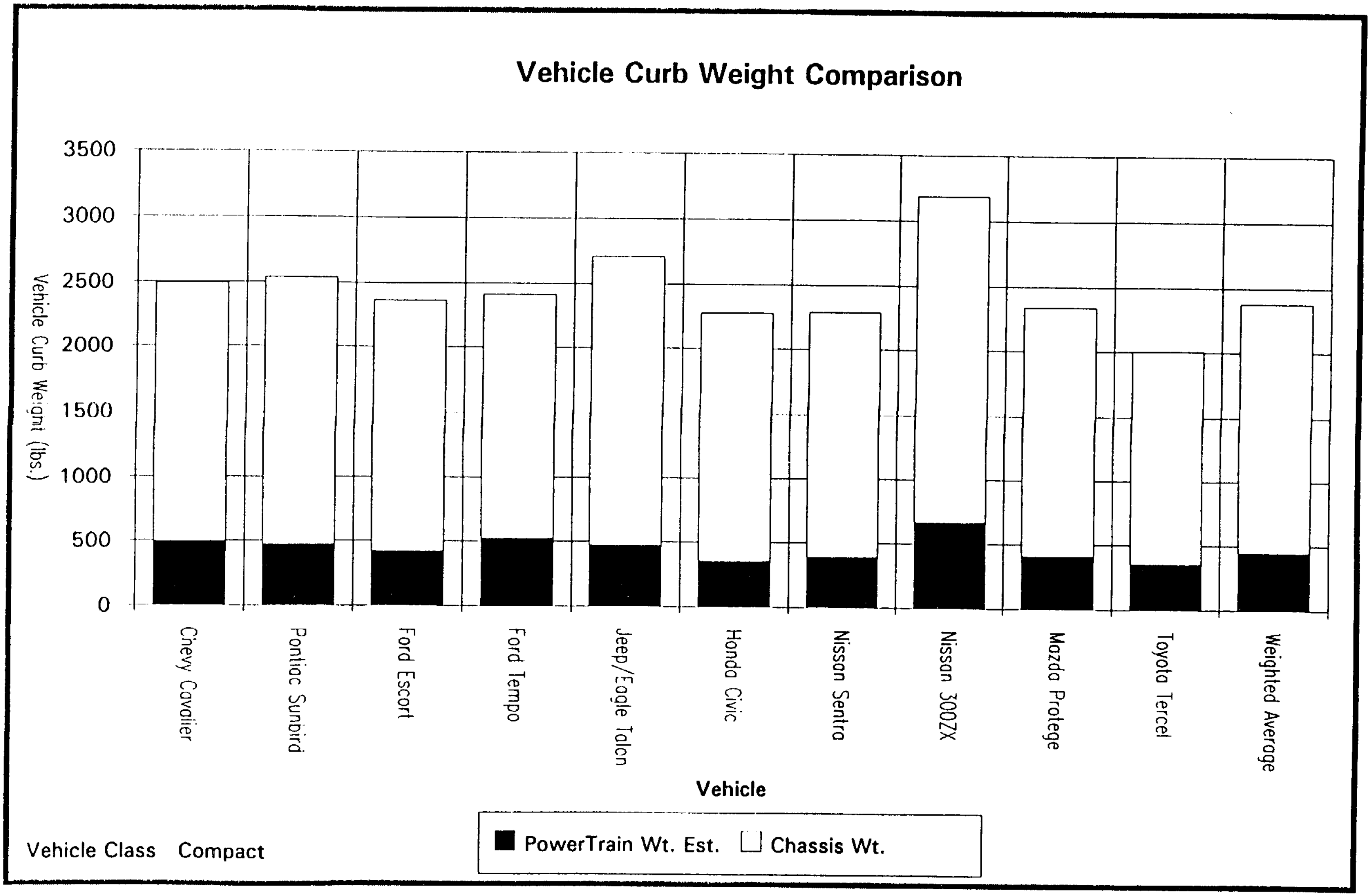

Vehicles Sold in 1991
350000
300000
250000
200000
150000
100000
50000
0
Number of Vehicles Sold in 1991
Buick Regal
Cutlass Supreme
Grand Prix
Sable
Taurus
Tracer
Accord
Weighted Average
Vehicle
Vehicle Class
Midsize

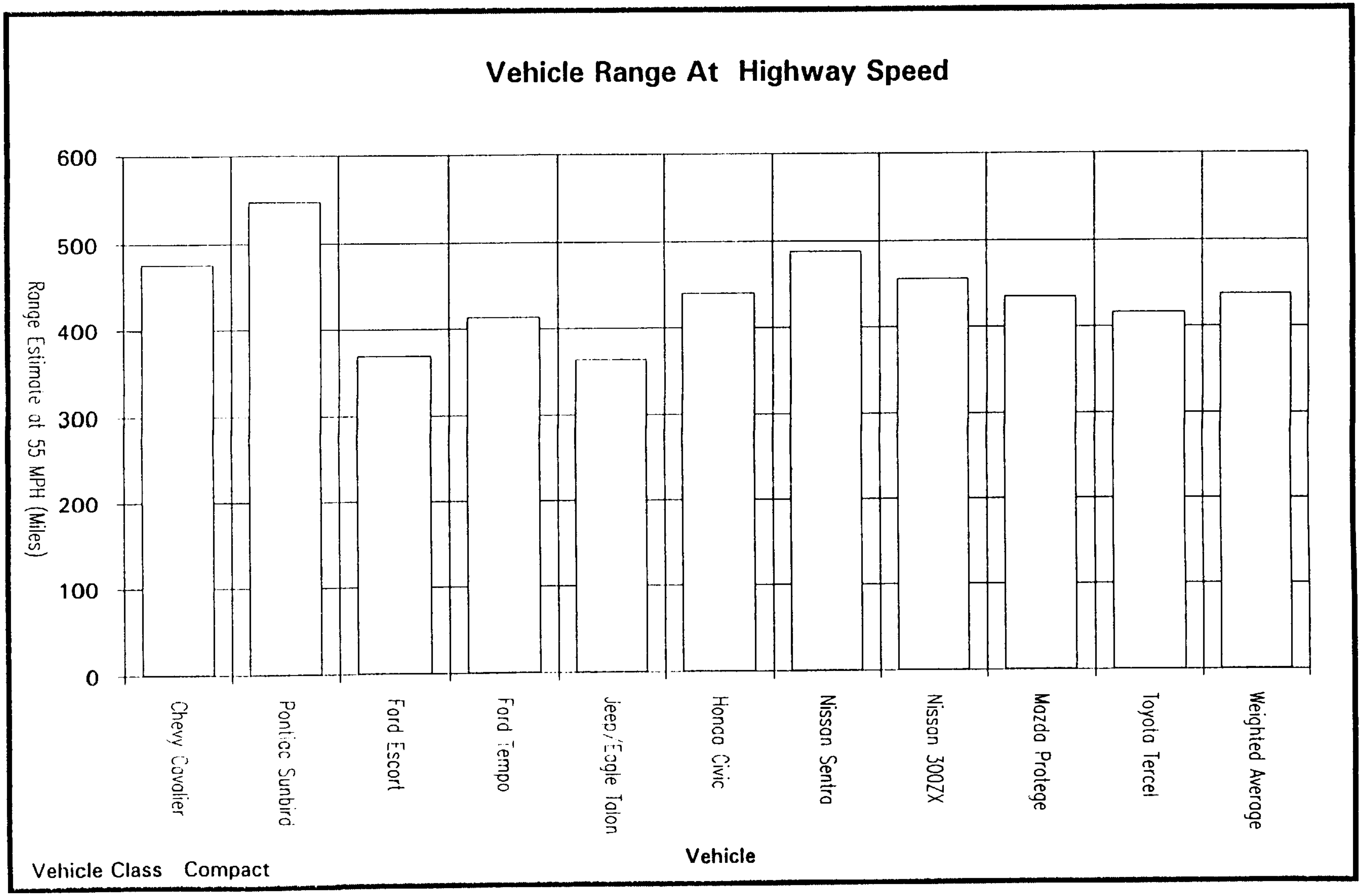


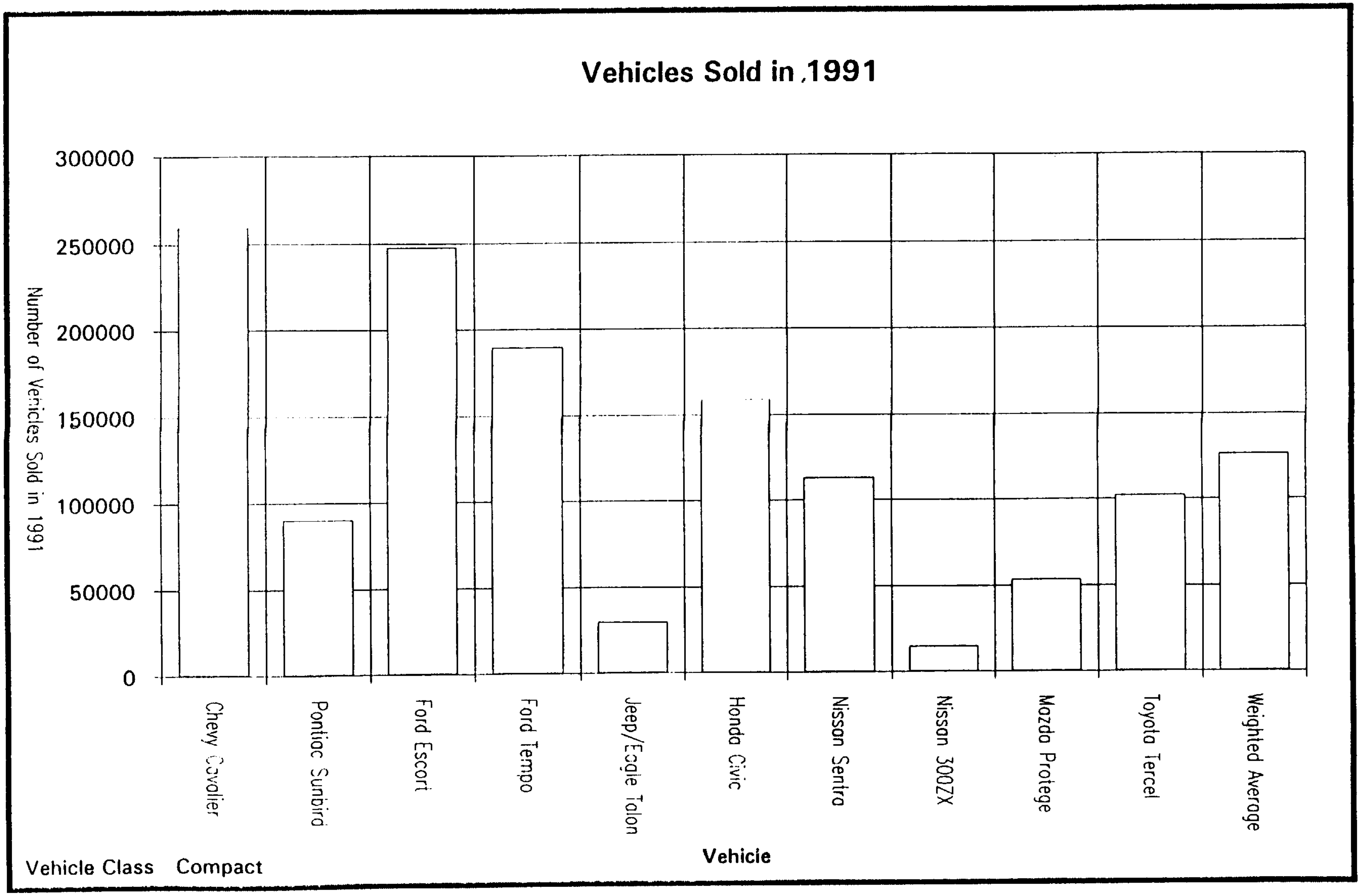
Vehicle Retail Price (1992)
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
Price Per Vehicle ($)
Buick Regal
Cutlass Supreme
Grand Prix
Sable
Taurus
Tracer
Accord
Weighted Average
Vehicle
Vehicle Class
Midsize

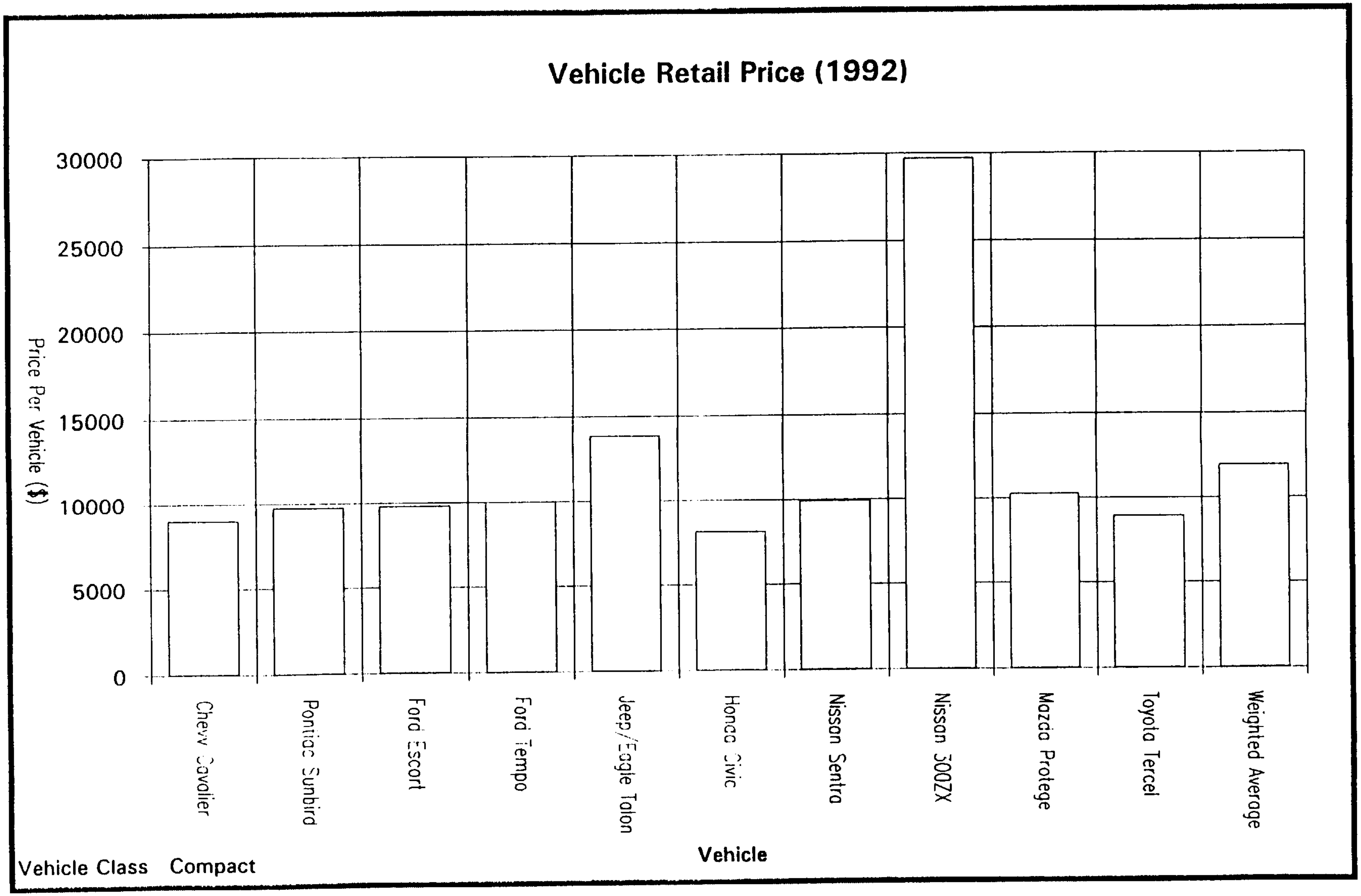

EPA Total Volume Index
120
100
80
60
40
20
0
EPA Volume Index, (cubic ft.)
Chevy Cavalier
Pontiac Sunbird
Ford Escort
Ford Tempo
Jeep/Eagle Talon
Honda Civic
Nissan Sentra
Nissan 300ZX
Mazda Protege
Toyota Tercel
Weighted Average
Vehicle
Vehicle Class Compact
Trunk
Passenger

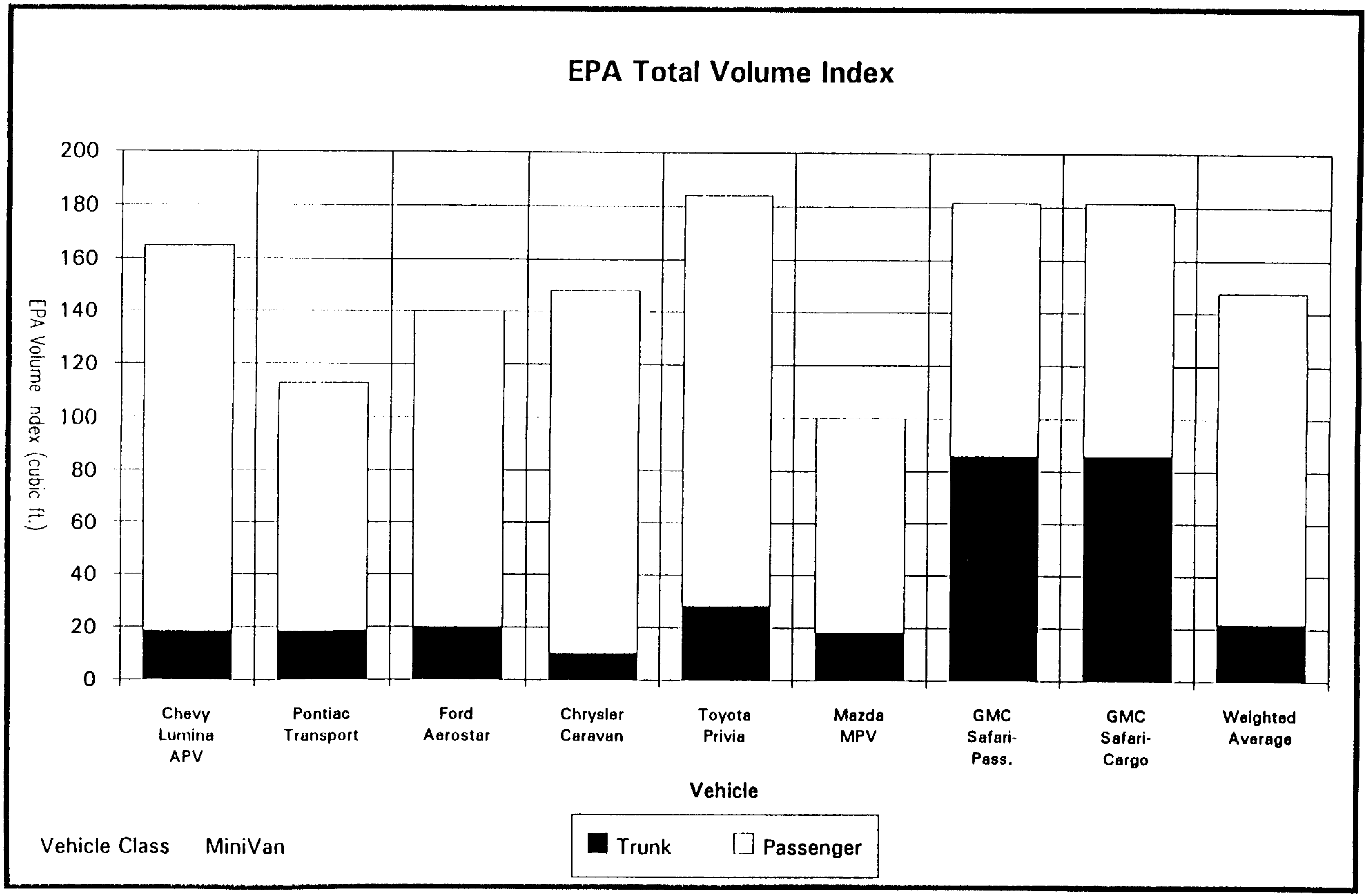

Shadow Area and Wheel Base
Shadow Area (Sq. ft.)
Wheel Base (in.)
84
82
80
78
76
74
72
70
68
66
104
102
100
98
96
94
92
90
88
Chevy Cavalier
Pontiac Sunbird
Ford Escort
Ford Tempo
Jeep/Eagle Talon
Honda Civic
Nissan Sentra
Nissan 300ZX
Mazda Protege
Toyota Tercel
Weighted Average
Vehicle
Shadow Area
Wheel Base
Vehicle Class Compact

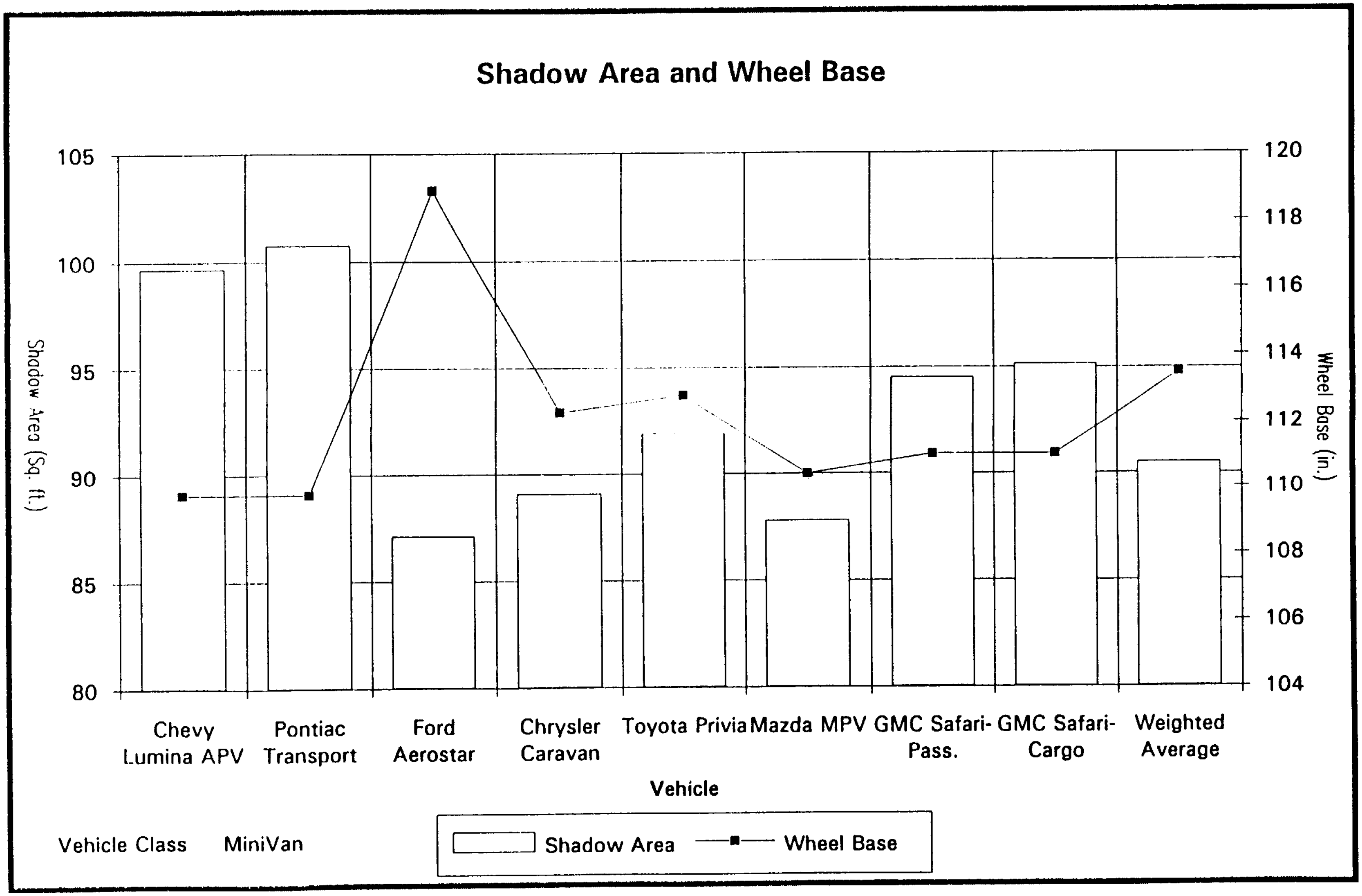

Vehicle Curb Weight Comparison
3500
3000
2500
2000
1500
1000
500
0
Vehicle Curb Weight (lbs.)
Chevy Cavalier
Pontiac Sunbird
Ford Escort
Ford Tempo
Jeep/Eagle Talon
Honda Civic
Nissan Sentra
Nissan 300ZX
Mazda Protege
Toyota Tercel
Weighted Average
Vehicle
PowerTrain Wt. Est.
Chassis Wt.
Vehicle Class Compact


Vehicle Range At Highway Speed
600
500
400
300
200
100
0
Range Estimate at 55 MPH (Miles)
Chevy Cavalier
Pontiac Sunbird
Ford Escort
Ford Tempo
Jeep/Eagle Talon
Honda Civic
Nissan Sentra
Nissan 300ZX
Mazda Protege
Toyota Tercel
Weighted Average
Vehicle
Vehicle Class Compact

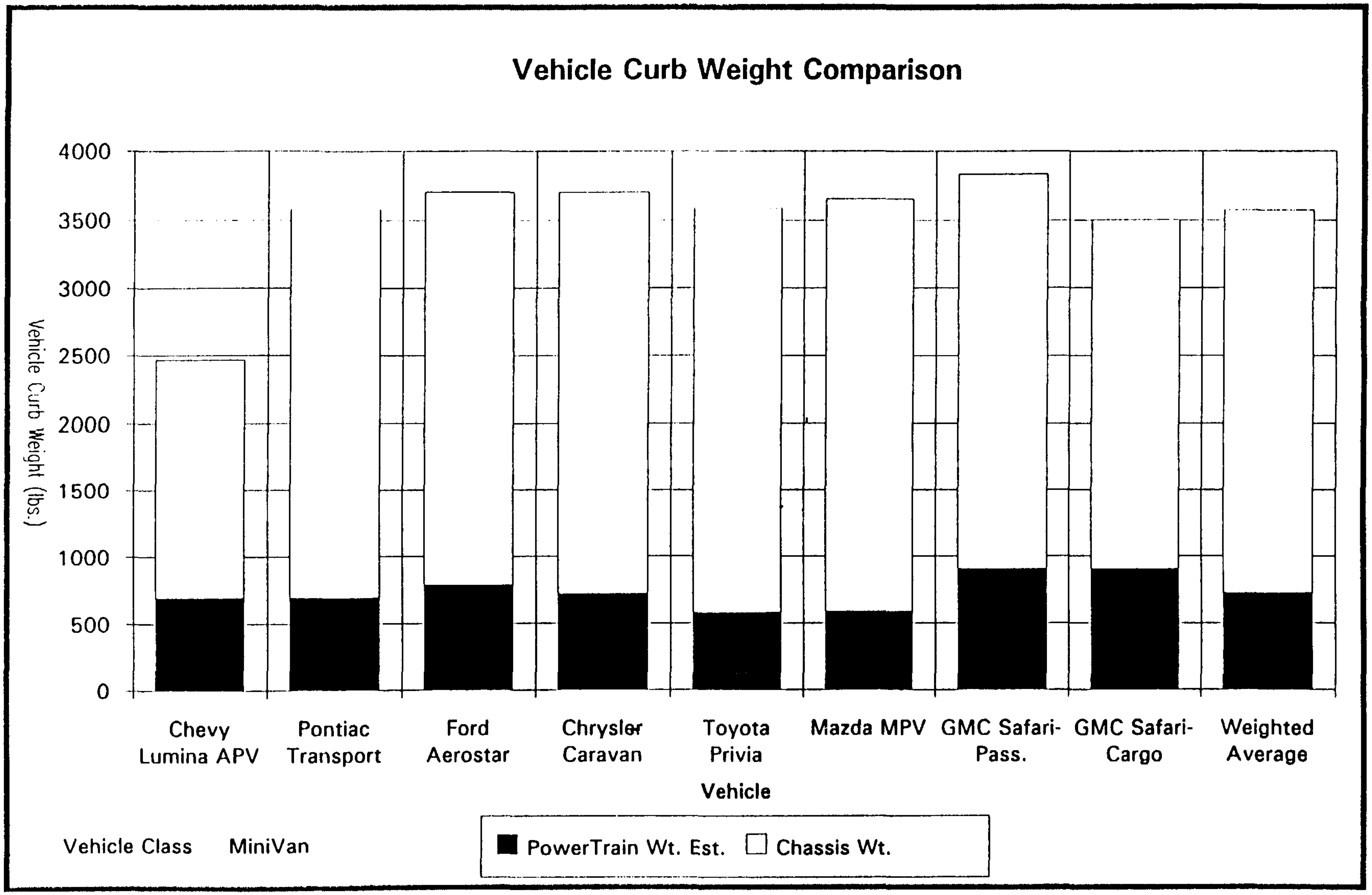

Vehicles Sold in ,1991
300000
250000
200000
150000
100000
50000
0
Number of Vehicles Sold in 1991
Chevy Cavalier
Pontiac Sunbird
Ford Escort
Ford Tempo
Jeep/Eagle Talon
Honda Civic
Nissan Sentra
Nissan 300ZX
Mazda Protege
Toyota Tercel
Weighted Average
Vehicle
Vehicle Class Compact


Vehicle Retail Price (1992)
Price Per Vehicle ($)
30000
25000
20000
15000
10000
5000
0
Chevy Cavalier
Pontiac Sunbird
Ford Escort
Ford Tempo
Jeep/Eagle Talon
Honda Civic
Nissan Sentra
Nissan 300ZX
Mazda Protege
Toyota Tercel
Weighted Average
Vehicle
Vehicle Class Compact

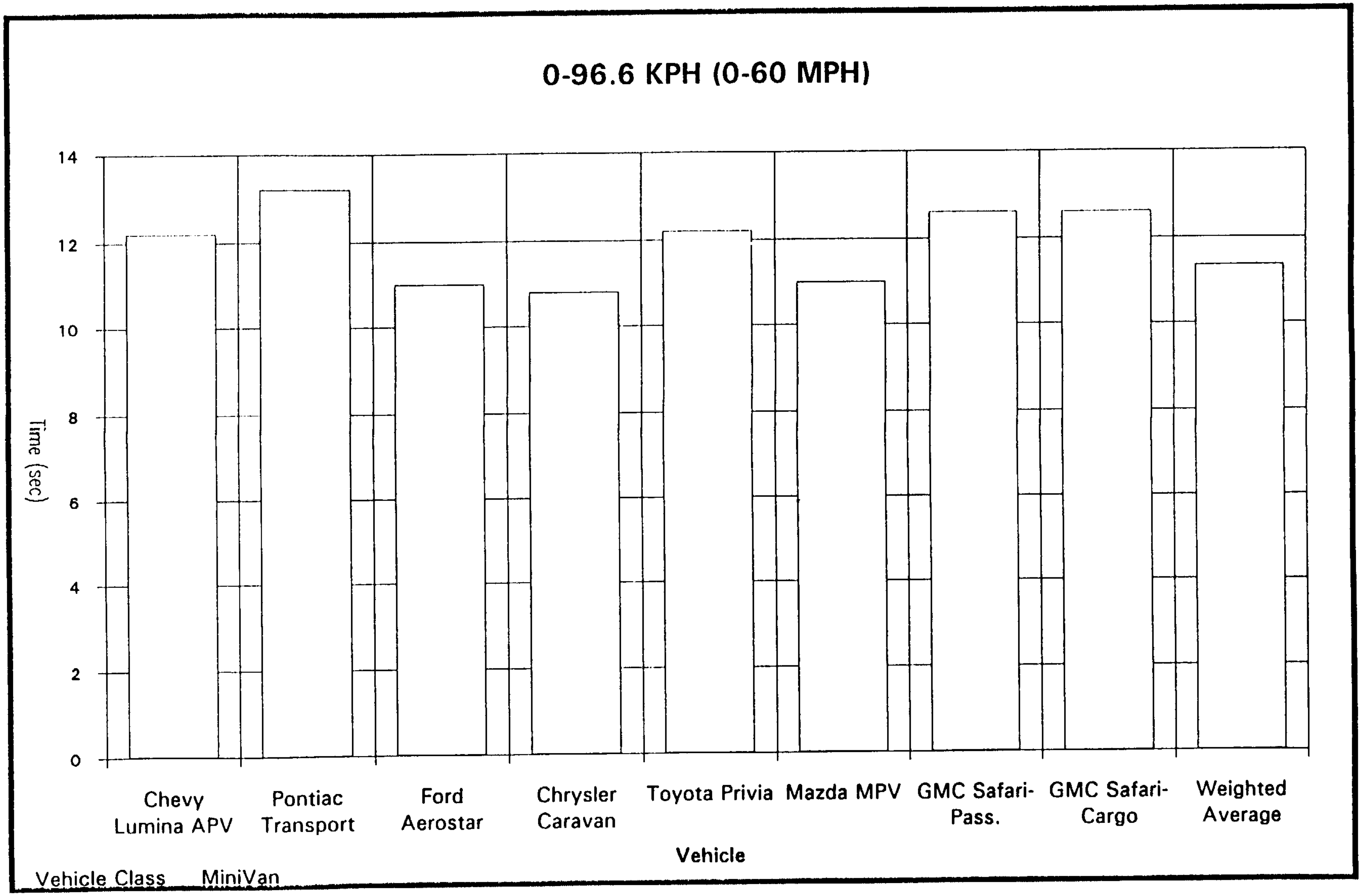

EPA Total Volume Index
200
180
160
140
120
100
80
60
40
20
0
EPA Volume ndex (cubic ft.)
Chevy Lumina APV
Pontiac Transport
Ford Aerostar
Chrysler Caravan
Toyota Privia
Mazda MPV
GMC Safari-Pass.
GMC Safari-Cargo
Weighted Average
Vehicle
Vehicle Class MiniVan
Trunk
Passenger

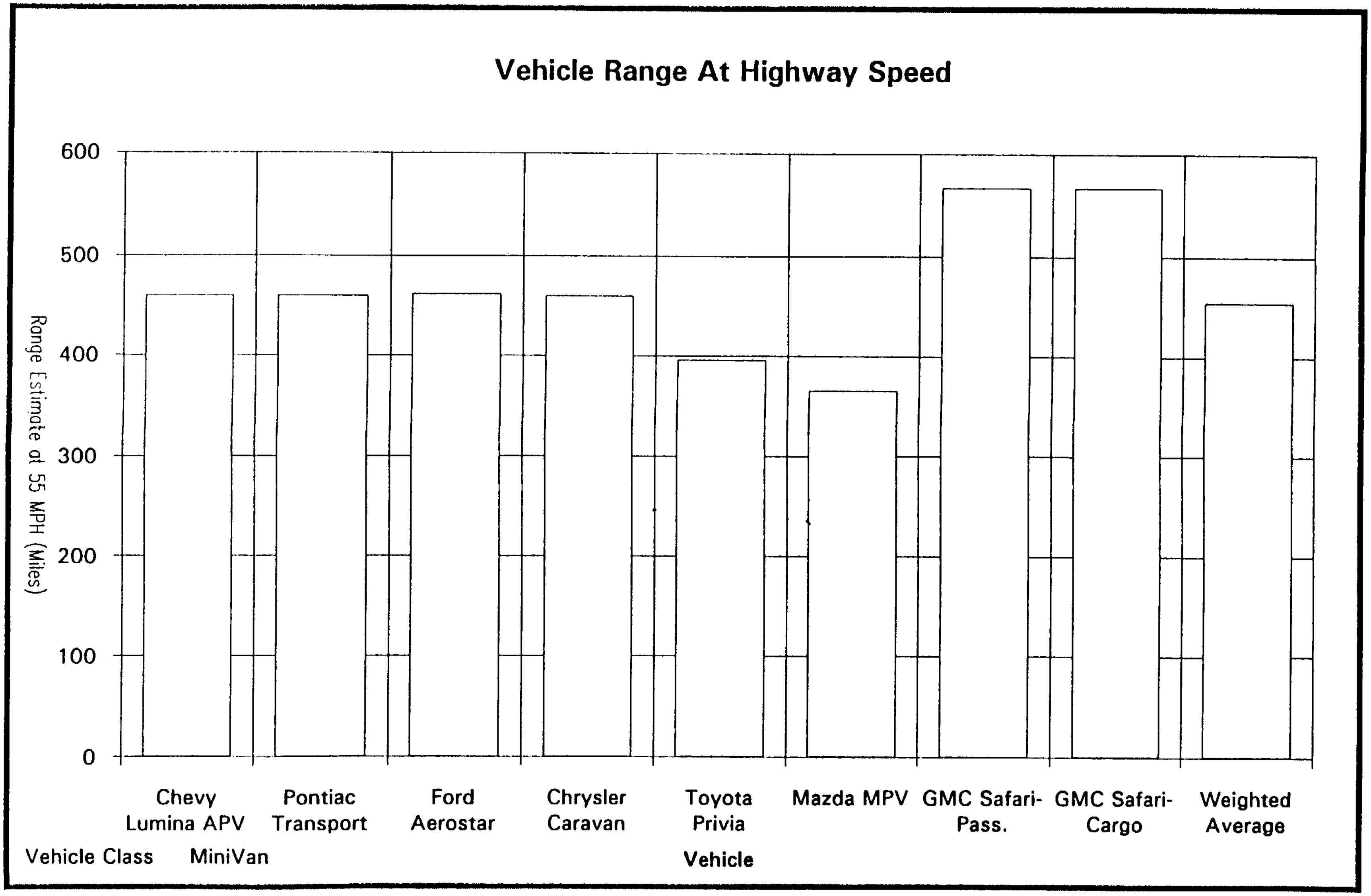


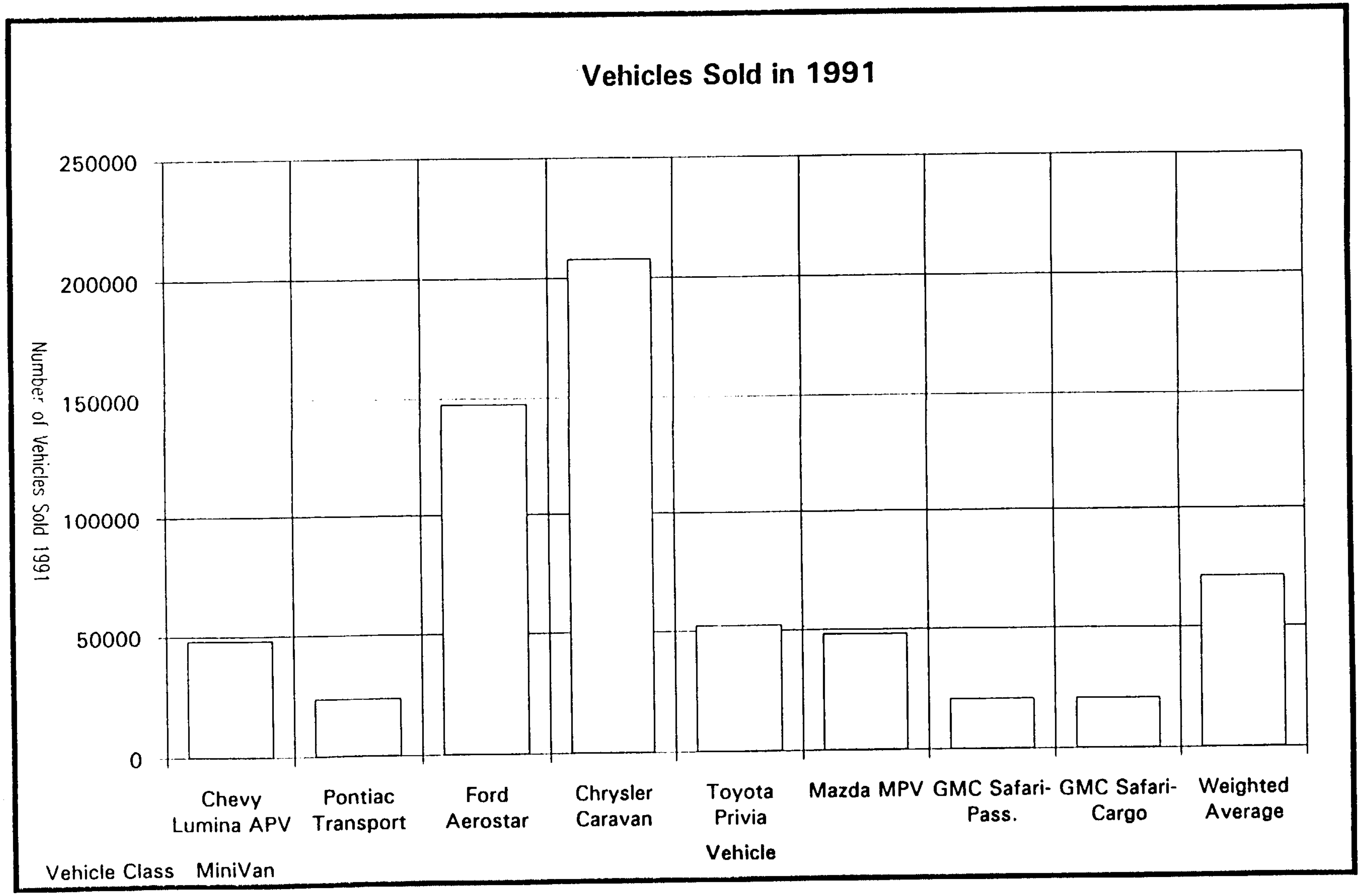
Shadow Area and Wheel Base
105
100
95
90
85
80
Shadow Area (Sq. ft.)
120
118
116
114
112
110
108
106
104
Wheel Base (in.)
Chevy Lumina APV
Pontiac Transport
Ford Aerostar
Chrysler Caravan
Toyota Privia
Mazda MPV
GMC Safari-Pass.
GMC Safari-Cargo
Weighted Average
Vehicle
Vehicle Class MiniVan
Shadow Area
Wheel Base



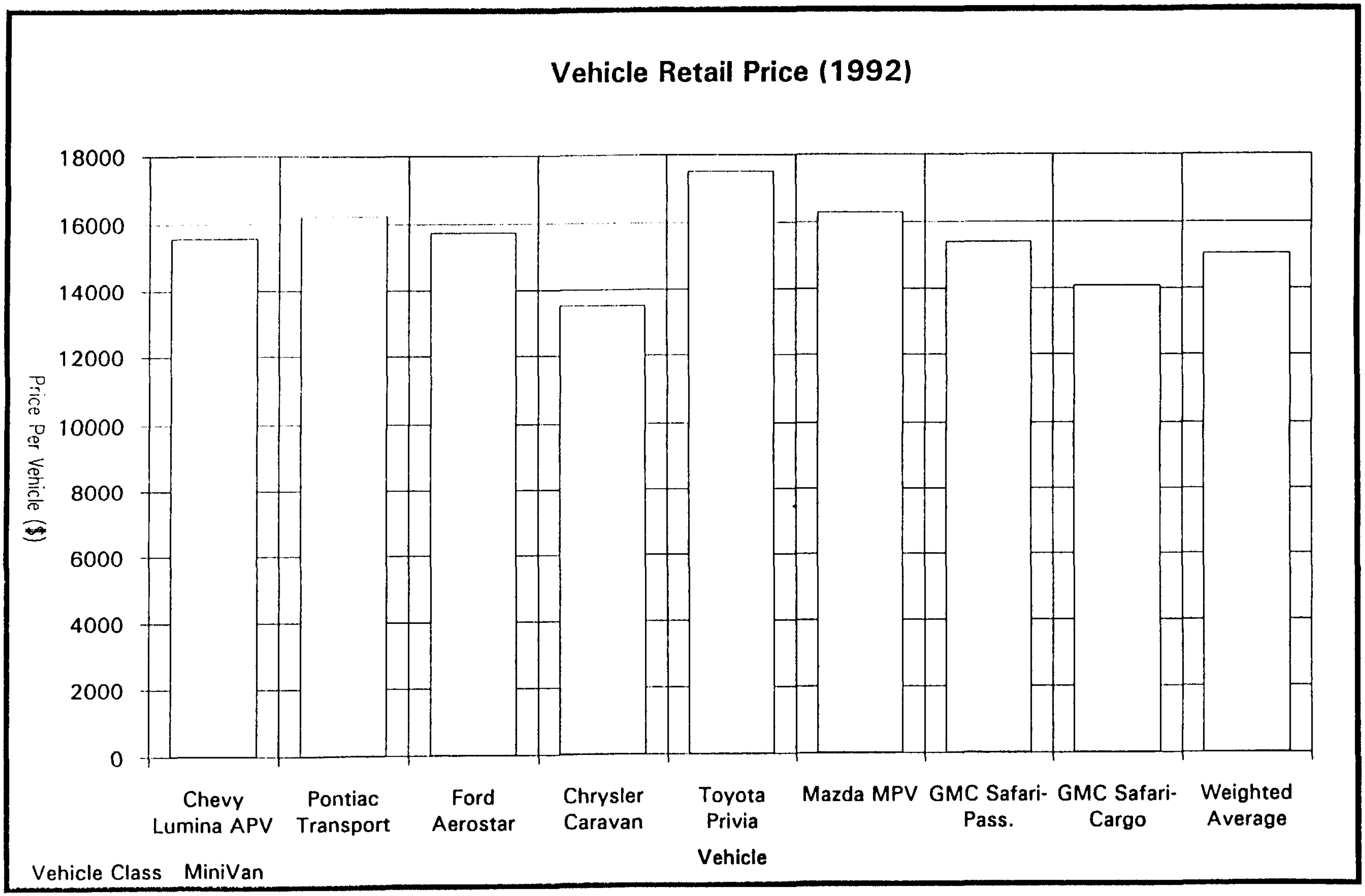
Vehicle Curb Weight Comparison
4000
3500
3000
2500
2000
1500
1000
500
0
Vehicle Curb Weight (lbs.)
Chevy Lumina APV
Pontiac Transport
Ford Aerostar
Chrysler Caravan
Toyota Privia
Mazda MPV
GMC Safari-Pass.
GMC Safari-Cargo
Weighted Average
Vehicle
Vehicle Class
MiniVan
PowerTrain Wt. Est.
Chassis Wt.


0-96.6 KPH (0-60 MPH)
Time (sec)
0
2
4
6
8
10
12
14
Chevy Lumina APV
Pontiac Transport
Ford Aerostar
Chrysler Caravan
Toyota Privia
Mazda MPV
GMC Safari-Pass.
GMC Safari-Cargo
Weighted Average
Vehicle
Vehicle Class
MiniVan


Vehicle Range At Highway Speed
Range Estimate at 55 MPH (Miles)
600
500
400
300
200
100
0
Chevy Lumina APV
Pontiac Transport
Ford Aerostar
Chrysler Caravan
Toyota Privia
Mazda MPV
GMC Safari-Pass.
GMC Safari-Cargo
Weighted Average
Vehicle Class
MiniVan
Vehicle



Vehicles Sold in 1991
250000
200000
150000
100000
50000
0
Number of Vehicles Sold 1991
Chevy Lumina APV
Pontiac Transport
Ford Aerostar
Chrysler Caravan
Toyota Privia
Mazda MPV
GMC Safari-Pass.
GMC Safari-Cargo
Weighted Average
Vehicle
Vehicle Class MiniVan


Vehicle Retail Price (1992)
Price Per Vehicle ($)
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
Chevy Lumina APV
Pontiac Transport
Ford Aerostar
Chrysler Caravan
Toyota Privia
Mazda MPV
GMC Safari-Pass.
GMC Safari-Cargo
Weighted Average
Vehicle
Vehicle Class MiniVan

Appendix B

Federal (EPA) Determined Urban and Highway Driving Cycles, Fuel Economy Adjustments, Composite Fuel Economy, and Energy Based Fuel Consumption

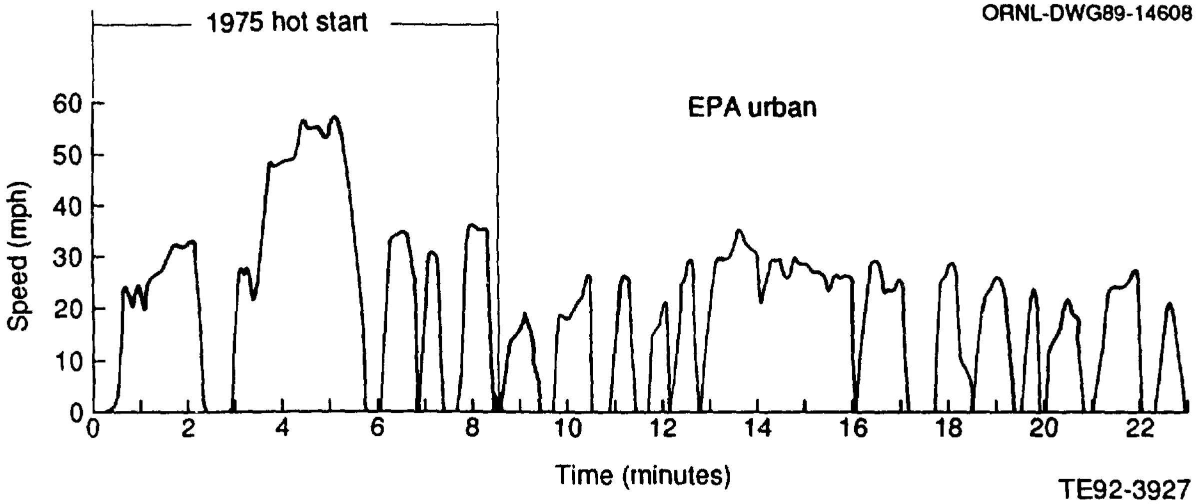


*Figure B-1. Urban driving cycle (length of cycle: 1372 sec; average speed: 19.8 mph).**

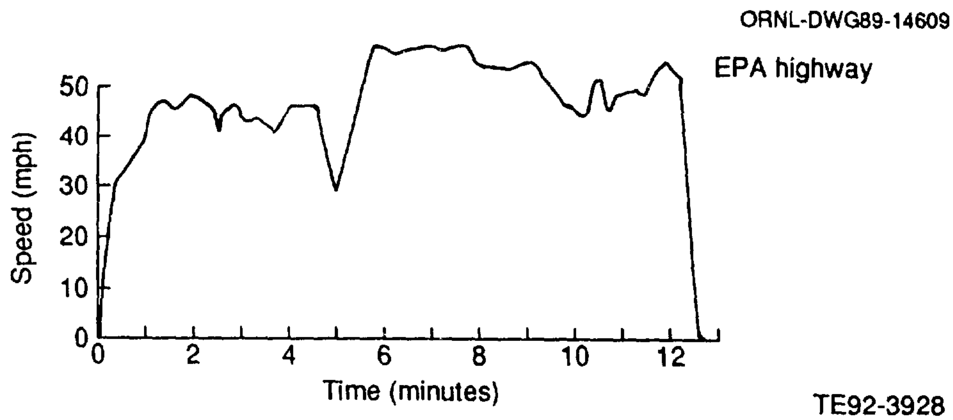


*Figure B-1. Highway driving cycle (length of cycle: 765 seconds; average speed: 48.5 mph).**

* Source: *Code of Federal Regulations*, 40CFR, "Subpart B - Fuel Economy Regulations for 1978 and Later Model Year Automobiles - Test Procedures," July 1, 1988 edition, p. 676.

EPA FUEL ECONOMY ADJUSTMENT

"To make the fuel economy numbers published by the EPA more useful to consumers, the laboratory test results obtained on the urban and highway driving schedules (FUDS and FHDS) are adjusted to account for the difference between controlled laboratory conditions and actual driving on the road. The laboratory fuel economy results are adjusted downward to arrive at the estimates used on the labels seen on new cars. The urban estimate is lowered by 10% and the highway estimate by 22% from the laboratory test results. Experience has proven that these adjustments cause the gas mileage estimates to correspond more closely to the actual fuel economy realized by the average driver."

— *1993 Mileage Guide*, U. S. Government Printing Office, DOE/CE-0019/12, October, 1992

COMPOSITE FUEL ECONOMY

The composite fuel economy for a vehicle is calculated based on the fuel economy achieved on the FUDS and the FHDS, as follows:

$$\text{Composite Fuel Economy} = \frac{1}{\dfrac{0.55}{\text{FUDS Economy}} + \dfrac{0.45}{\text{FHDS Economy}}}$$

Note that composite fuel economy is therefore biased towards the urban driving cycle. The calculation assumes that 55% of the fuel is consumed in urban driving and 45% in highway driving.

ENERGY BASED FUEL CONSUMPTION

The energy consumption for a vehicle is calculated based on the equation shown below. This equation was taken from a paper presented by Frank Black at the October 1991 Annual Automotive Technology Development Contractors' Coordination Meeting held in Dearborn, MI.

Fuel Heating Values	kJ/kg	kJ/L
Methanol	20,003.3	15,888.2
Gasoline	43,495.5	32,612.6
Diesel	42,565.2	36,514.9
M85	23,527.1	18,396.8

Fuel Density	kg/L
Methanol	0.79
Gasoline	0.74
Diesel	0.86

$$\text{kW-hr/km} = \frac{\text{fuel heating value (kJ/kg)} \;*\; \text{fuel density (kg/L)}}{3600\ \text{(kJ/kWh)} \;*\; \text{fuel economy (km/L)}}$$

Appendix C

Electrochemical Engine System Estimated Costs

ECE SYSTEM ESTIMATED COSTS

The approach used to arrive at a future, high volume market cost estimate involved

- selection of a projected system performance level
- computation of the fuel processor, fuel cell stack, compressor-expander, and heat rejection and water management physical sizes
- computation of the number of stack cells, etc
- selection of the type, quantity, and price of the materials required to manufacture the system components

Assembly costs of the system were based on design for manufacturing concepts using automated manufacturing equipment. The projected costs are approximate and are based on the best information now available to the GM/LANL JDC design team. Estimates are in 1992 U.S. dollars and assume a high volume market.

The performance goals used in the cost estimate assumed an ECE system capable of continuous operation at 60-kW. The fuel cell stack was assumed to have a 929 cm^2 (1 ft^2) active area capable of continuous operation at 1100 mA/cm^2 @ 0.7V per cell. Eighty-six cells are therefore required to continuously produce 60-kW. At peak power conditions, 2200 mA/cm^2 @ 0.5V, the system can produce ~90-kW for limited time periods. The time duration allowed at the peak power condition is limited by heat exchanger and fuel processing design considerations. This situation is similar to many ICE systems, which also have limited peak power operational capability.

Voltage at the 60-kW level is approximately 60V. This voltage can be doubled, for example, by halving the fuel cell active area and electrically connecting the two smaller stacks, each having 86 cells, with one-half the active area, in series. A configuration such as this is accompanied by a very slight increase in overall volume and cost (additional end plates, connections, and manifolding) but the higher voltage, 120V at the 60-kW level, results in a less sophisticated, and hence, less expensive, inverter design.

Although any number of trade-off configurations are possible, the ECE system cost projections were estimated using the original configuration (single fuel cell stack, 86 cells, with 929 cm^2(1 ft^2) active area) because that configuration is based on an actual preliminary design. The single design/cost exception to the schematic and preliminary design described earlier (Figure 4-2 in Section IV) involves the turboexpander unit. Some system operating conditions (part-load or sudden deceleration) favor decoupling the expander and compressor portions of the turboexpander. Consequently, these two devices are no longer considered to be connected by a rigid shaft but, rather, through an electromechanical clutch. Depending on the operating condition, the clutch is either engaged or disengaged. During the latter condition the expander drives a dc generator which is used to produce power for battery charging, etc. During this operating condition, the compressor is driven by an electric motor, and power for the electric motor flows either from the fuel cell stack or from the battery pack. During clutch engagement the dc generator is disabled and the turboexpander provides a portion of the power required to operate the compressor.

The cost projections (Table C-2) were based on the following set of specifications in Table C-1 for a nominal continuously operating 60-kW system.

Table C-1.
60-kW ECE system specifications and operating conditions.

Fuel Cell Stack	
Type of fuel cell	PEM
Membrane	best available
Electrodes/catalysts	optimized for reformate/air pt alloy loading ≤ 0.2 mg/cm^2 per cell
Bipolar plate material(s)	coated aluminum (graphite, TiB_2, polymer, etc)
Reactants	reformate and air
Reactant pressures	≤ 3 atmospheres absolute
Reactant stoichiometries	reformate ≤ 1.4; air ≤ 2.0
Stack operating temperature	$\geq 90^{o}C$
Gas recirculation pumps Anode Cathode	 100 scfm reformate 250 scfm air
Cell polarization Voltage/current density	100 A/ft^2 @ 0.9V 1000 A/ft^2 @ 0.7V 2000 A/ft^2 @ 0.5V
Cell activation area	≥ 0.5 ft^2 (cost projection based on 1 ft^2)
System (stack) power rating (continuous operation)	60-kW
System (stack) lifetime	> 3,500 hr

Fuel Processor	
Type of processor	Recirculating gas (convectively heated) reformer with series two stage shift zone, multistage PROX unit
Catalysts Reformer Shifters PROX	 CuO-ZnO CuO-ZnO Pt (or other noble metal)
Catalyst support	monolithic (400 channel/in^2) right cylinder alumina with catalyst washcoat - AC Rochester design
Air injection valves	proportional control - AC Rochester design
Combustor	annular multifuel Allison combustor (ceramic)
Heat exchangers/vaporizers	stainless steel - Harrison Radiator/AC Rochester design
Pumps/injector system	stainless steel/plastic - AC Rochester design
Recirculating fan/motor/seal (water pressurized)	250 scfm @ 3 in. H_2O pressure, stainless steel straight blade mixed flow blower

Table C-1 (continued).

Heat Rejection, Water and Fuel Management, and Controls	
Cooling water pump	plastic 10 gpm - AC Rochester design
Radiator	corrosion protected aluminum
Condenser	corrosion protected aluminum
Fuel tank	stainless steel
Water tank	plastic
Control computers	EPROM based - GMRVS/Allison design
Control valves	proportional control - AC Rochester design

System Auxiliaries	
Scroll expander/dc generator	200 scfm/6-kW - Harrison Radiator/AC Rochester/Delco Remy design
Scroll compressor/dc electric motor (variable speed)	215 scfm/15-kW - Harrison Radiator/AC Rochester/Delco Remy design
Electromechanical clutch	mild steel/Cu coil
Valve body	cast/machined aluminum

Table C-2.
60-kW ECE customer cost specifications.

	Cost
Fuel Cell Stack	
Bipolar and end plates	$532
Membranes and current collectors	$886
Gas recirulcation pumps	$184
Outer containment cannister and 2 end caps/manifolding	$150
Fuel cell stack total	$1752
$/(60-kW)	$29.2
$/(peak-kW)	$20.9
Fuel Processor	
Fluid injection systems	$138
Combustor/ignition system	$200
Heat exchanges and catalyst monoliths	$288
Shift zone components	$118
PROX components	$183
Outer containment canister and 2 end caps/manifolding	$150
Fuel processor total	$1077
$/(60-kW)	$18.0
$/(peak-kW)	$12.8
Heat Rejection and Water Management System	
Water handling system	$42
Condenser/radiator	$117
Tanks	$36
Heat rejection and water management system total	$195
$/(60-kW)	$3.3
$/(peak-kW)	$2.3
System Auxiliaries Total	$875
$/(60-kW)	$14.6
$/(peak-kW)	$10.4
ECE System Total Cost	$3,899
$/(60-kW)	$65.1
$/(peak-kW)	$46.4

The estimated total costs of the PEM ECE power system, therefore, are ~ $65/kW on a continuously operating rated basis or, equivalently, ~ 46/kW on a peak power rated basis. The latter figure is a better comparison to production ICE automotive engines as their costs are calculated as a function of peak power rating. Cost projections for a PEM ECE power system in the size range required for the FCVs considered in this study indicate that the ECE cost is made up as follows:

• Fuel Cell Stack	44.9%
• Fuel Processor	27.6%
• Water and Thermal Management System	5.1%
• System Auxiliaries	22.4%

If cost comparisons are made to current 1992 common, high volume, high technology production ICE automotive engines, some important qualifications must be recognized

- Today's ICE will not meet projected future emission standards and, if the ICE can be made to do so, it will carry a possibly significant cost premium. Thus, the comparison of a future ECE (ULEV or near ZEV) to the cost of today's ICE (that is not capable of meeting such stringent emission requirements) is not entirely valid.

- Comparing equivalent power loses some meaning because of the very different torque/response characteristics of the ICE versus electric traction systems.

- Comparing only power plant costs can be misleading because other power train costs are necessary in both the ICE and the ECE scenarios. These additional costs, plus overall vehicle costs must eventually be considered in regard to customer appeal.

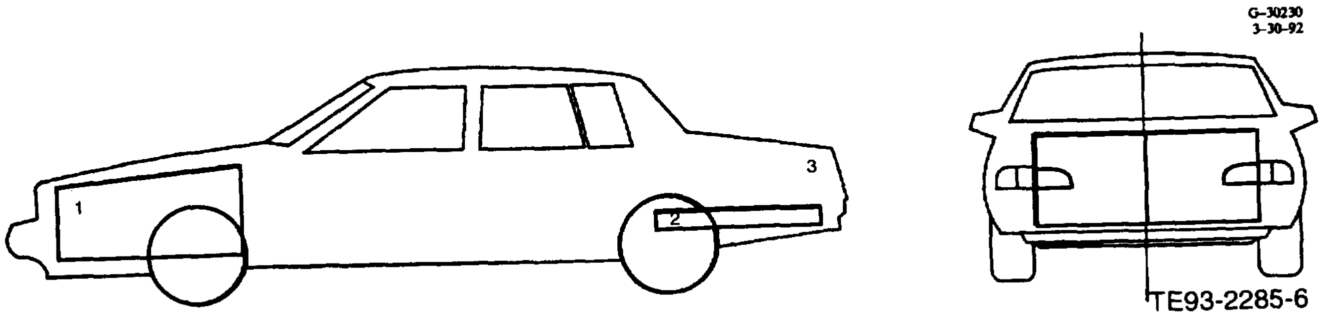
- The costs compared here are initial purchase costs only. Life-cycle costs or total cost of ownership, including such elements as fuel cost, maintenance, insurance, licensing, etc, are also important to the customer. There may be substantial life-cycle cost differences for an ECE power system in comparison to today's (or tomorrow's) ICE. Some of these types of costs will be addressed in the Trade-off Analysis Report.

Appendix D

Specifications and Evaluated Performance and Energy Use Characteristics of Vehicles Analyzed in the Evaluation Matrix

Note: **rolling resistance coefficients for the tires are 0.01 N/kN for the urban bus and 0.0098 N/kN for all other vehicles**

Table D-1.
Current production large car.



Vehicle Data

EPA classification	large
Vehicle type	Cadillac Fleetwood
Curb weight (kg/lb)	1,655/3,642
Test weight (kg/lb)	1,792/3,942
Wheelbase (cm/in.)	289/113.8
Overall length (cm/in.)	528/208.0
Overall width (cm/in.)	186/73.4
Frontal area (m^2/ft^2)	2.32/25.0
Drag coefficient (C_d)	0.42
Number of passengers	6

Performance

Top speed (km/hr / mph)	169/105
0 to 96.6 km/hr (60 mph)(sec)	cold 9.0
	warm 9.0
Gradeability (% grade)	
Short term maximum negotiable	30.0%
Long term @ 96.6 km/hr	>6%
Range on FHDS(km/mi)	724/450
Start-up & drive away time	<1 Sec
Long term storage (days)	
Ambient-normal start (21°C/70°F)	35

EPA Volume Available

Passenger (m^3/ft^3)	3.04/107.2
Trunk/cargo (m^3/ft^3)	0.513/18.1
Total volume (m^3/ft^3)	3.55/125.3
Fuel tank size (L/gal)	68.1/18.0

Energy Usage

Fuel economy (gasoline)	
FHDS-highway(km/L / mpg)	10.64/25.
FUDS-city (km/L / mpg)	6.80/16.0
Composite energy (55/45) usage (kW-hr/km)	1.100

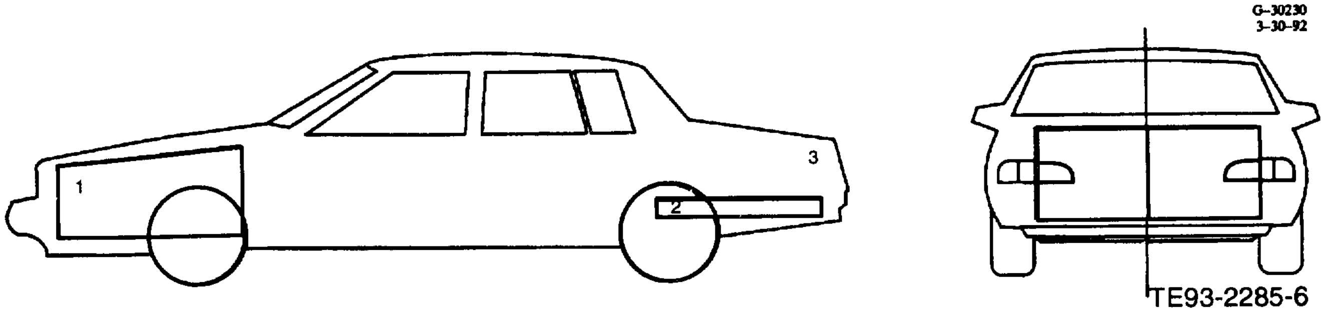
Components

	Rated power (kW)	Weight (kg/lb)	Volume (m^3/ft^3)	Location
Battery pack	NA	NA	NA	NA
Electric drive system	NA	NA	NA	NA
Electrochemical engine	NA	NA	NA	NA
ICE and transmission	150	440/968	0.345/12.2	1
Fuel tank	NA	61/135	0.068/2.4	2

NA = not applicable

TE92-3929

Table D-2.
Maximum performance large car FCV.



Vehicle Data

EPA classification	large
Vehicle type	conceptual FCV
Curb weight (kg/lb)	2,439/5,365
Test weight (kg/lb)	2,575/5,665
Wheelbase (cm/in)	289/113.8
Overall length (cm/in.)	528/208.0
Overall width (cm/in.)	186/73.4
Frontal area (m^2/ft^2)	2.32/25.0
Drag coefficient (C_d)	0.42
Number of passengers	6

EPA Volume Available

Passenger (m^3/ft^3)	3.04/107.2
Trunk/cargo (m^3/ft^3)	0.127/4.5
Total volume (m^3/ft^3)	3.16/111.7
Fuel tank size (L/gal)	68.1/18.0

Performance

Top speed (km/hr / mph)	169/105
0 to 96.6 km/hr (60 mph)(sec)	cold 8.8
	warm 7.4
Gradeability (% grade)	
Short term maximum negotiable	28.9%
Long term @ 96.6 km/hr	>6%
Range on FHDS (km/mi)	510/317
Start-up & drive-away time	<1 Sec
Long term storage (days)	
Ambient-normal start (21°C/70°F)	35

Energy Usage

Fuel economy (gasoline)	
FHDS-highway (km/L / mpg)	7.46/17.6
FUDS-city (km/L / mpg)	6.29/14.8
Composite energy (55/45) usage (kW-hr/km)	0.648
Energy usage compared to ICE	59%

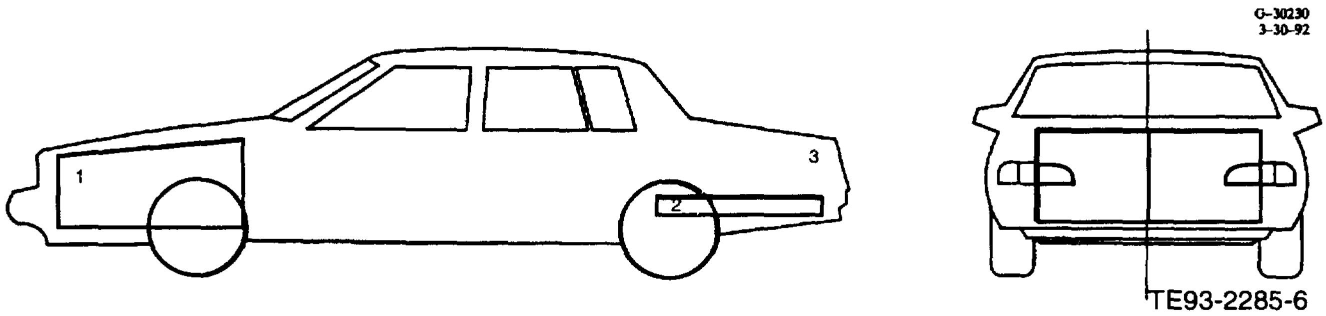
Components

	Rated power (kW)	Weight (kg/lb)	Volume (m^3/ft^3)	Location
Battery pack	168	731/1,608	0.340/12.0	1
Electric drive system	270	330/729	0.576/20.1	1
Electrochemical engine	80	296/651	0.487/17.2	3/2
ICE and transmission	NA	NA	NA	NA
Fuel tank	NA	65/142	0.068/2.4	2

NA = not applicable

TE92-3930

Table D-3.
Similar performance large car FCV.



Vehicle Data	
EPA classification	large
Vehicle type	conceptual FCV
Curb weight (kg/lb)	1,889/4,156
Test weight (kg/lb)	2,025/4,456
Wheelbase (cm/in)	289/113.8
Overall length (cm/in.)	528/208.0
Overall width (cm/in.)	186/73.4
Frontal area (m^2/ft^2)	2.32/25.0
Drag coefficient (C_d)	0.42
Number of passengers	6

EPA Volume Available	
Passenger (m^3/ft^3)	3.04/107.2
Trunk/cargo (m^3/ft^3)	0.479/16.9
Total volume (m^3/ft^3)	3.51/124.1
Fuel tank size (L/gal)	68.1/18.0

Performance	
Top speed (km/hr / mph)	156/97
0 to 96.6 km/hr (60 mph)(sec)	cold 17.4
	warm 9.6
Gradeability (% grade)	
Short term maximum negotiable	18.7%
Long term @ 96.6 km/hr	>6%
Range on FHDS (km/mi)	603/374
Start-up & drive-away time	<1 Sec
Long term storage (days)	
Ambient-normal start (21°C/70°F)	NA

Energy Usage	
Fuel economy (gasoline)	
FHDS-highway (km/L / mpg)	8.85/20.8
FUDS-city (km/L / mpg)	7.94/18.7
Composite energy (55/45) usage (kW-hr/km)	0.526
Energy usage compared to ICE	48%

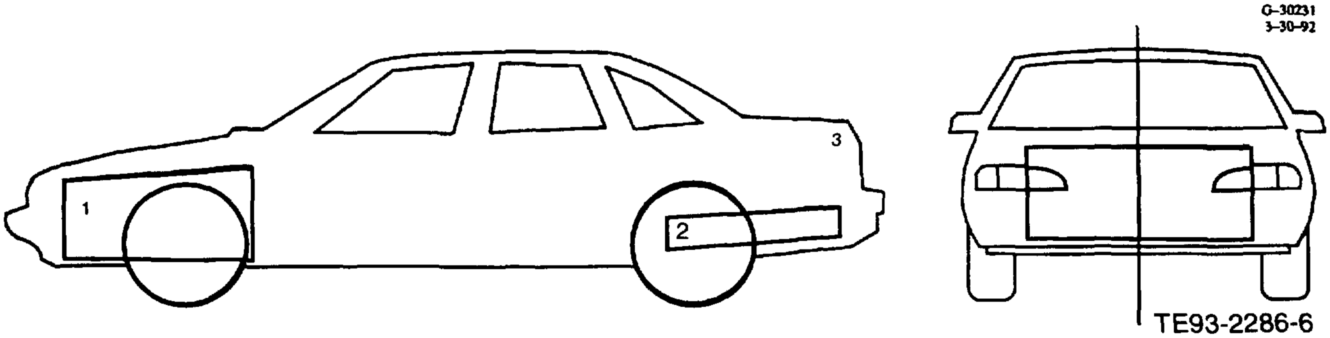
Components

	Rated power (kW)	Weight (kg/lb)	Volume (m^3/ft^3)	Location
Battery pack	67	291/641	0.136/4.8	2/3
Electric drive system	180	220/486	0.384/13.4	1
Electrochemical engine	80	296/651	0.487/17.2	1
ICE and transmission	NA	NA	NA	NA
Fuel tank	NA	65/142	0.068/2.4	2

NA = not applicable

TE92-3931

Table D-4.
Current production mid-size car.



Vehicle Data		Performance	
EPA classification	mid-sized	Top speed (km/hr / mph)	177/110
Vehicle type	Buick Regal	0 to 96.6 km/hr (60 mph)(sec)	cold 9.2
Curb weight (kg/lb)	1,539/3,385		warm 9.2
Test weight (kg/lb)	1,675/3,685	Gradeability (% grade)	
Wheelbase (cm/in)	273/107.5	Short term maximum negotiable	30.0%
Overall length (cm/in.)	498/196.0	Long term @ 96.6 km/hr	>6%
Overall width (cm/in.)	184/72.5	Range on FHDS (km/mi)	744/462
Frontal area (m^2/ft^2)	1.98/21.3	Start-up & drive-away time	<1 Sec
Drag coefficient (C_d)	0.35	Long term storage (days)	
Number of passengers	6	Ambient-normal start (21°C/70°F)	35

EPA Volume Available		Energy Usage	
Passenger (m^3/ft^3)	2.88/101.7	Fuel economy (gasoline)	
Trunk/cargo (m^3/ft^3)	0.447/15.8	FHDS-highway (km/L / mpg)	11.90/28.
Total volume (m^3/ft^3)	3.30/116.5	FUDS-city (km/L / mpg)	8.06/19.0
Fuel tank size (L/gal)	62.5/16.5	Composite energy (55/45) usage (kW-hr/km)	0.946

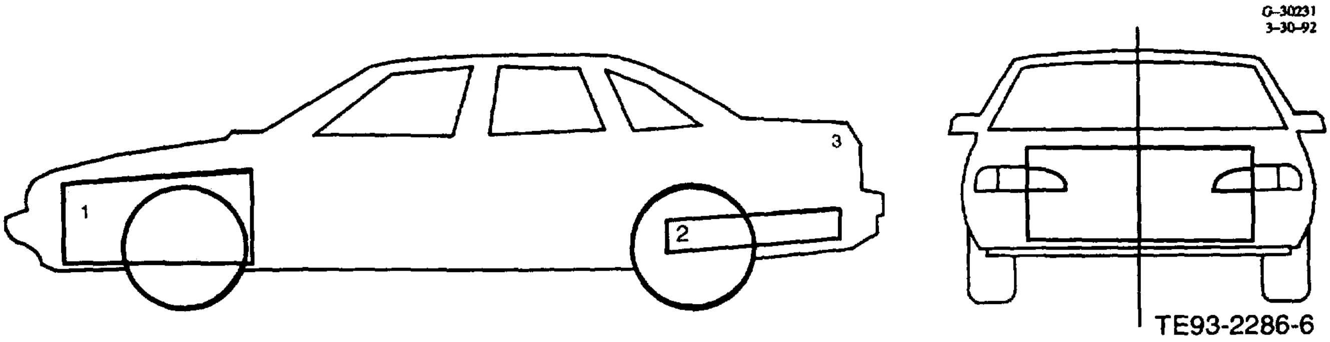
Components

	Rated power (kW)	Weight (kg/lb)	Volume (m^3/ft^3)	Location
Battery pack	NA	NA	NA	NA
Electric drive system	NA	NA	NA	NA
Electrochemical engine	NA	NA	NA	NA
ICE and transmission	128	345/759	0.246/8.7	1
Fuel tank	NA	56/124	0.063/2.2	2

NA = not applicable

TE92-3932

Table D-5.
Maximum performance mid-size car FCV.



Vehicle Data		**Performance**	
EPA classification	mid-sized	Top speed (km/hr / mph)	158/98
Vehicle type	conceptual FCV	0 to 96.6 km/hr (60 mph)(sec)	cold 9.4
Curb weight (kg/lb)	2,342/5,153		warm 7.6
Test weight (kg/lb)	2,479/5,453	Gradeability (% grade)	
Wheelbase (cm/in)	273/107.5	Short term maximum negotiable	27.0%
Overall length (cm/in.)	498/196.0	Long term @ 96.6 km/hr	>6%
Overall width (cm/in.)	184/72.5	Range on FHDS (km/mi)	523/325
Frontal area (m^2/ft^2)	1.98/21.3	Start-up & drive-away time	<1 Sec
Drag coefficient (C_d)	0.35	Long term storage (days)	
Number of passengers	6	Ambient-normal start (21°C/70°F)	NA
EPA Volume Available		**Energy Usage**	
Passenger (m^3/ft^3)	2.88/101.7	Fuel economy (gasoline)	
Trunk/cargo (m^3/ft^3)	0.130/4.6	FHDS-highway (km/L / mpg)	8.40/19.7
Total volume (m^3/ft^3)	3.01/106.3	FUDS-city (km/L / mpg)	6.54/15.4
Fuel tank size (L/gal)	62.5/16.5	Composite energy (55/45) usage (kW-hr/km)	0.613
		Energy usage compared to ICE	64%

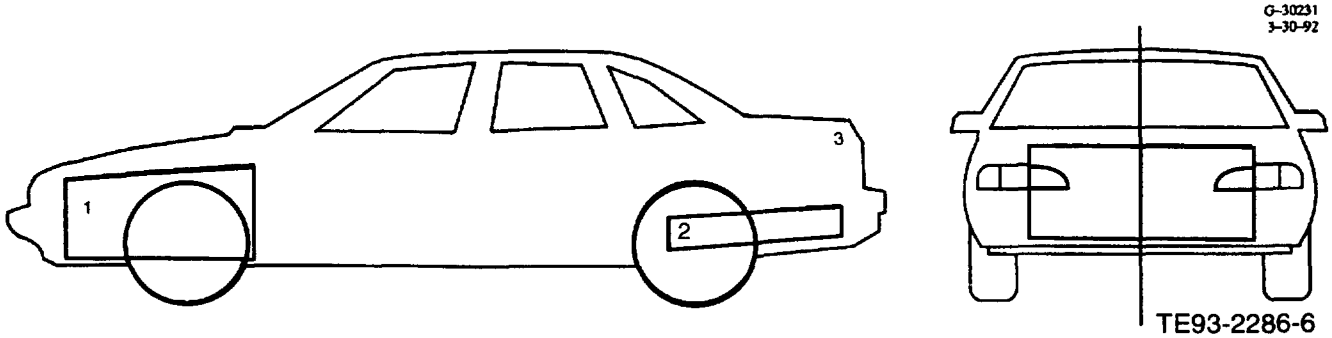
Components

	Rated power (kW)	Weight (kg/lb)	Volume (m^3/ft^3)	Location
Battery pack	168	657/1,445	0.306/10.8	1
Electric drive system	270	330/729	0.576/20.1	1
Electrochemical engine	80	296/651	0.487/17.2	3/2
ICE and transmission	NA	NA	NA	NA
Fuel tank	NA	59/130	0.063/2.2	2

NA = not applicable

TE92-3933

Table D-6.
Similar performance mid-sized car FCV.



Vehicle Data		Performance	
EPA classification	large	Top speed (km/hr / mph)	158/98
Vehicle type	conceptual FCV	0 to 96.6 km/hr (60 mph)(sec)	cold 16.8
Curb weight (kg/lb)	1,867/4,107		warm 10.0
Test weight (kg/lb)	2,003/4,407	Gradeability (% grade)	
Wheelbase (cm/in)	273/107.5	Short term maximum negotiable	18.7%
Overall length (cm/in.)	498/196.0	Long term @ 96.6 km/hr	>6%
Overall width (cm/in.)	184/72.5	Range on FHDS (km/mi)	621/386
Frontal area (m^2/ft^2)	1.98/21.3	Start-up & drive-away time	<1 Sec
Drag coefficient (C_d)	0.35	Long term storage (days)	
Number of passengers	6	Ambient-normal start (21°C/70°F)	NA

EPA Volume Available		Energy Usage	
Passenger (m^3/ft^3)	2.88/101.7	Fuel economy (gasoline)	
Trunk/cargo (m^3/ft^3)	0.130/4.6	FHDS-highway (km/L / mpg)	9.90/23.4
Total volume (m^3/ft^3)	3.01/106.3	FUDS-city (km/L / mpg)	8.13/19.0
Fuel tank size (L/gal)	62.5/16.5	Composite Energy (55/45) usage	
		(kW-hr/km)	0.496
		Energy usage compared to ICE	53%

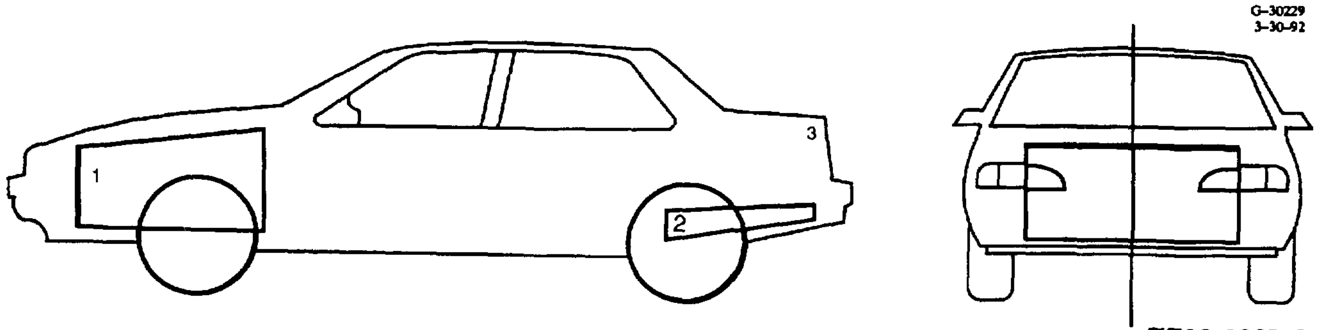
Components

	Rated power (kW)	Weight (kg/lb)	Volume (m^3/ft^3)	Location
Battery pack	67	291/641	0.136/4.8	1
Electric drive system	180	220/486	0.384/13.4	1
Electrochemical engine	80	296/651	0.487/17.2	3/2
ICE and transmission	NA	NA	NA	NA
Fuel tank	NA	59/130	0.063/2.2	2

NA = not applicable

TE92-3934

Table D-7.
Current production compact car.



TE93-2287-6

Vehicle Data		Performance	
EPA classification	compact	Top speed (km/hr / mph)	169/105
Vehicle type	Chevrolet Cavalier	0 to 96.6 km/hr (60 mph)(sec)	cold 11.0
Curb weight (kg/lb)	1,132/2,491		warm 11.0
Test weight (kg/lb)	1,369/2,791	Gradeability (% grade)	
Wheelbase (cm/in)	257/101.3	Short term maximum negotiable	30.0%
Overall length (cm/in.)	463/182.3	Long term @ 96.6 km/hr	>6%
Overall width (cm/in.)	168/66.3	Range on FHDS (km/mi)	766/476
Frontal area (m^2/ft^2)	1.88/20.2	Start-up & drive-away time	<1 Sec
Drag coefficient (C_d)	0.35	Long term storage (days)	
Number of passengers	5	Ambient-normal start (21°C/70°F)	35

EPA Volume Available		Energy Usage	
Passenger (m^3/ft^3)	2.64/93.2	Fuel economy (gasoline)	
Trunk/cargo (m^3/ft^3)	0.368/13.0	FHDS-highway (km/L / mpg)	14.93/35.0
Total volume (m^3/ft^3)	3.01/106.2	FUDS-city (km/L / mpg)	10.20/24.0
Fuel tank size (L/gal)	51.5/13.6	Composite Energy (55/45) usage (kW-hr/km)	0.751

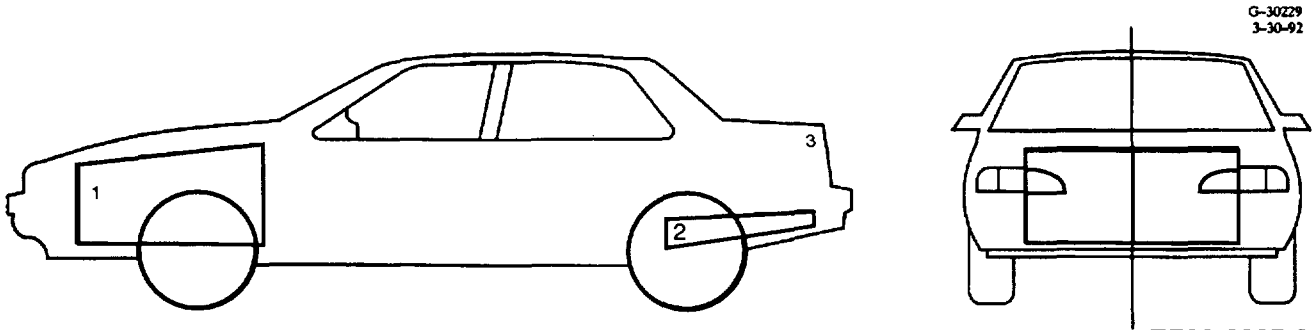
Components

	Rated power (kW)	Weight (kg/lb)	Volume (m^3/ft^3)	Location
Battery pack	NA	NA	NA	NA
Electric drive system	NA	NA	NA	NA
Electrochemical engine	NA	NA	NA	NA
ICE and transmission	83	230/505	0.201/7.1	1
Fuel tank	NA	46/102	0.052/1.8	2

NA = not applicable

TE92-3935

Table D-8.
Maximum performance compact car FCV.



Vehicle Data		Performance	
EPA classification	compact	Top speed (km/hr / mph)	146/91
Vehicle type	conceptual FCV	0 to 96.6 km/hr (60 mph)(sec)	cold 8.8
Curb weight (kg/lb)	1,551/3,412		warm 7.4
Test weight (kg/lb)	1,678/3,712	Gradeability (% grade)	
Wheelbase (cm/in)	257/101.3	Short term maximum negotiable	25.3%
Overall length (cm/in.)	463/182.3	Long term @ 96.6 km/hr	>6%
Overall width (cm/in.)	168/66.3	Range on FHDS (km/mi)	608/378
Frontal area (m^2/ft^2)	1.88/20.2	Start-up & drive-away time	<1 Sec
Drag coefficient (C_d)	0.35	Long term storage (days)	
Number of passengers	5	Ambient-normal start (21°C/70°F)	NA

EPA Volume Available		Energy Usage	
Passenger (m^3/ft^3)	2.64/93.2	Fuel economy (gasoline)	
Trunk/cargo (m^3/ft^3)	0.181/6.4	FHDS-highway (km/L / mpg)	11.76/27.8
Total volume (m^3/ft^3)	2.82/99.6	FUDS-city (km/L / mpg)	9.62/22.5
Fuel tank size (L/gal)	51.5/13.6	Composite energy (55/45) usage (kW-hr/km)	0.419
		Energy usage compared to ICE	56%

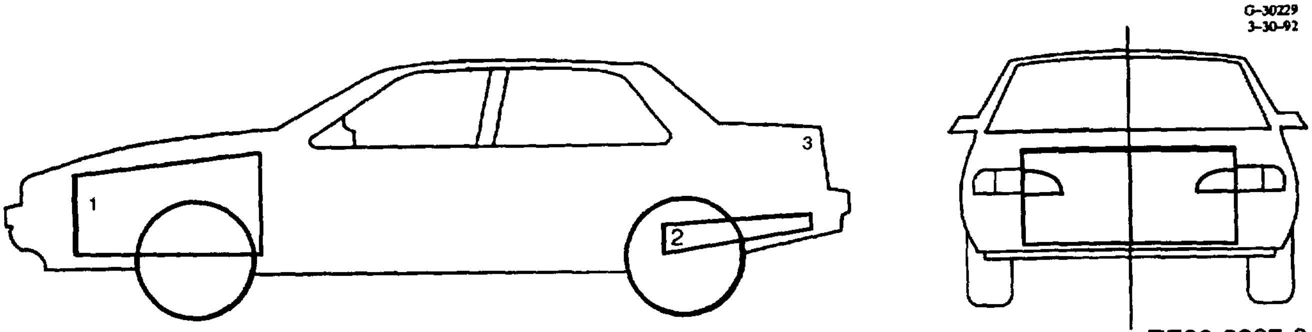
Components

	Rated Power (kW)	Weight (kg/lb)	Volume (m^3/ft^3)	Location
Battery pack	92	400/880	0.186/6.6	1
Electric drive system	135	165/364.5	0.288/10.05	1
Electrochemical engine	50	217/478	0.305/10.8	3/2
ICE and transmission	NA	NA	NA	NA
Fuel tank	NA	49/108	0.052/1.8	2

NA = not applicable

TE92-3936

Table D-9.
Similar performance compact car FCV.



Vehicle Data		Performance	
EPA classification	compact	Top speed (km/hr / mph)	146/91
Vehicle type	conceptual FCV	0 to 96.6 km/hr (60 mph)(sec)	cold 20.0 warm 11.0
Curb weight (kg/lb)	1,320/2,905		
Test weight (kg/lb)	1,457/3,205	Gradeability (% grade)	
Wheelbase (cm/in)	257/101.3	Short term maximum negotiable	15.9%
Overall length (cm/in.)	463/182.3	Long term @ 96.6 km/hr	>6%
Overall width (cm/in.)	168/66.3	Range on FHDS (km/mi)	665/413
Frontal area (m^2/ft^2)	1.88/20.2	Start-up & drive-away time	<1 Sec
Drag coefficient (C_d)	0.35	Long term storage (days)	
Number of passengers	5	Ambient-normal start (21°C/70°F)	NA

EPA Volume Available		Energy Usage	
Passenger (m^3/ft^3)	2.64/93.2	Fuel economy (gasoline)	
Trunk/cargo (m^3/ft^3)	0.215/7.6	FHDS-highway (km/L / mpg)	12.99/30.4
Total volume (m^3/ft^3)	2.85/100.8	FUDS-city (km/L / mpg)	11.11/29.1
Fuel tank size (L/gal)	51.5/13.6	Composite energy (55/45) usage (kW-hr/km)	0.370
		Energy usage compared to ICE	49%

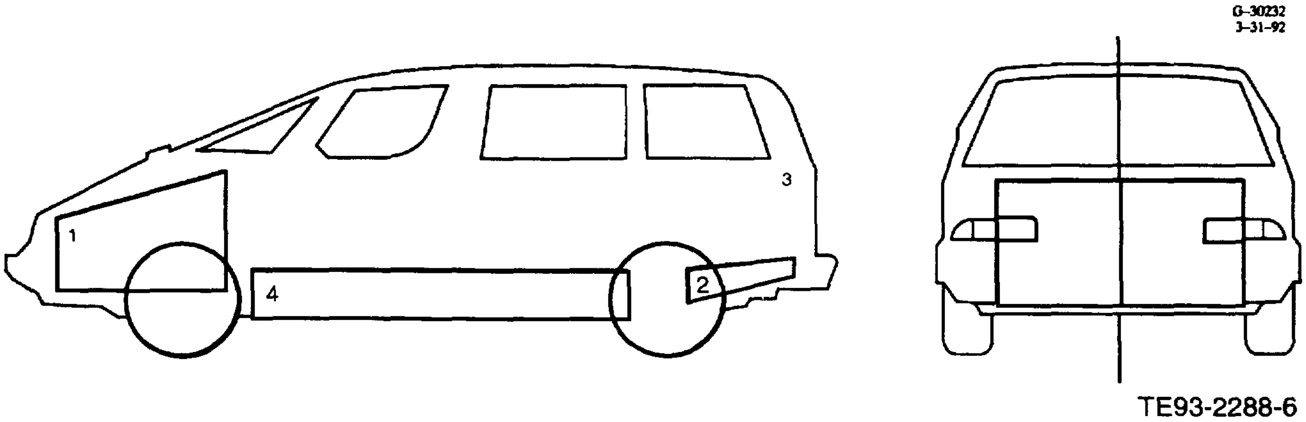
Components

	Rated power (kW)	Weight (kg/lb)	Volume (m^3/ft^3)	Location
Battery pack	42	183/402	0.085/3.0	1
Electric drive system	135	165/364.5	0.288/10.05	1
Electrochemical engine	45	204/449	0.275/9.7	3/2
ICE and transmission	NA	NA	NA	NA
Fuel tank	NA	49/108	0.052/1.8	2

NA = not applicable

TE92-3937

Table D-10.
Current production mini-van vehicle.



Vehicle Data		Performance	
EPA classification	mini-van	Top speed (km/hr / mph)	169/105
Vehicle type	Chevrolet APV	0 to 96.6 km/hr (60 mph)(sec)	cold 12.2
Curb weight (kg/lb)	1,498/3,295		warm 12.2
Test weight (kg/lb)	1,634/3,595	Gradeability (% grade)	
Wheelbase (cm/in)	279/109.8	Short term maximum negotiable	30.0%
Overall length (cm/in.)	493/194.2	Long term @ 96.6 km/hr	>6%
Overall width (cm/in.)	188/73.9	Range on FHDS (km/mi)	740/460
Frontal area (m^2/ft^2)	2.72/29.3	Start-up & drive-away time	<1 Sec
Drag coefficient (C_d)	0.33	Long term storage (days)	
Number of passengers	7	Ambient-normal start (21°C/70°F)	35

EPA Volume Available		Energy Usage	
Passenger (m^3/ft^3)	4.15/146.5	Fuel economy (gasoline)	
Trunk/cargo (m^3/ft^3)	0.521/18.4	FHDS-highway (km/L / mpg)	9.80/23.0
Total volume (m^3/ft^3)	4.67/164.9	FUDS-city (km/L / mpg)	7.63/18.0
Fuel tank size (L/gal)	75.7/20.0	Composite energy (55/45) usage (kW-hr/km)	1.053

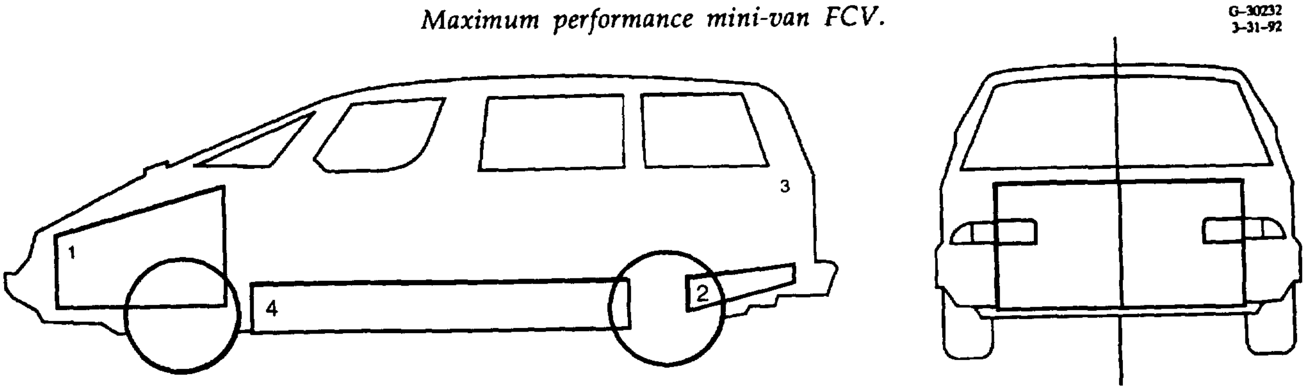
Components

	Rated power (kW)	Weight (kg/lb)	Volume (m^3/ft^3)	Location
Battery pack	NA	NA	NA	NA
Electric drive system	NA	NA	NA	NA
Electrochemical engine	NA	NA	NA	NA
ICE and transmission	90	314/692	0.235/8.3	1
Fuel tank	NA	68/150	0.076/2.7	2

NA = not applicable

TE92-3938

Table D-11.
Maximum performance mini-van FCV.



Vehicle Data		Performance	
EPA classification	mini-van	Top speed (km/hr / mph)	145/90
Vehicle type	conceptual FCV	0 to 96.6 km/hr (60 mph)(sec)	cold 12.0
Curb weight (kg/lb)	2,149/4,727		warm 10.2
Test weight (kg/lb)	2,285/5,027	Gradeability (% grade)	
Wheelbase (cm/in)	279/109.8	Short term maximum negotiable	23.1%
Overall length (cm/in.)	493/194.2	Long term @ 96.6 km/hr	>6%
Overall width (cm/in.)	188/73.9	Range on FHDS (km/mi)	628/390
Frontal area (m^2/ft^2)	2.72/29.3	Start-up & drive-away time	<1 Sec
Drag coefficient (C_d)	0.33	Long term storage (days)	
Number of passengers	7	Ambient-normal start (21°C/70°F)	NA

EPA Volume Available		Energy Usage	
		Fuel economy (gasoline)	
Passenger (m^3/ft^3)	4.15/146.5	FHDS-highway (km/L / mpg)	8.26/19.5
Trunk/cargo (m^3/ft^3)	0.521/18.4	FUDS-city (km/L / mpg)	6.58/15.5
Total volume (m^3/ft^3)	4.67/164.9	Composite energy (55/45) usage (kW-hr/km)	0.604
Fuel tank size (L/gal)	75.7/20.0	Energy usage compared to ICE	57%

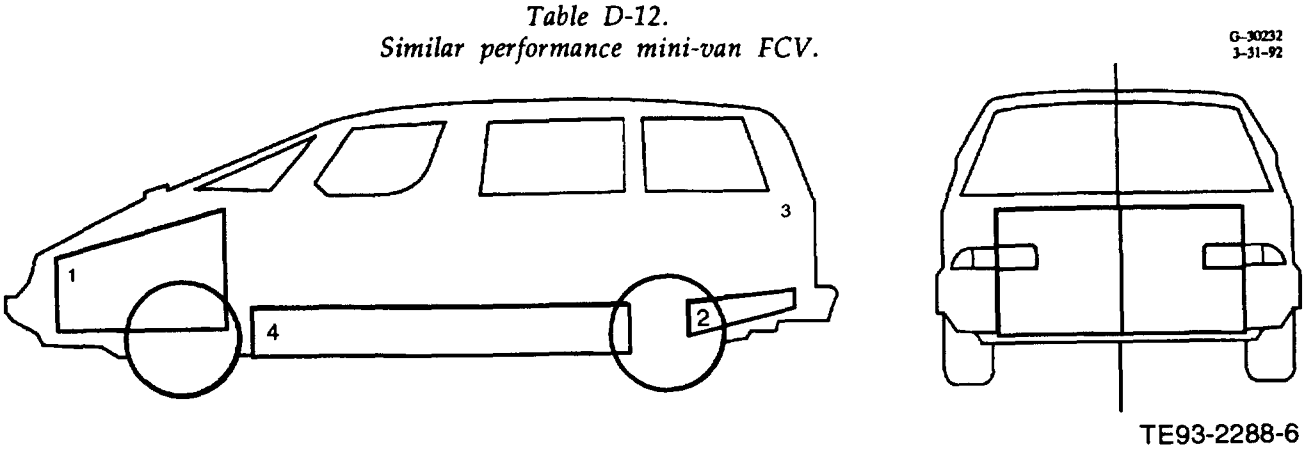
Components

	Rated power (kW)	Weight (kg/lb)	Volume (m^3/ft^3)	Location
Battery pack	134	583/1,282	0.271/9.6	4
Electric drive system	180	220/486	0.384/13.4	1
Electrochemical engine	80	296/651	0.487/17.2	4
ICE and transmission	NA	NA	NA	NA
Fuel tank	NA	72/158	0.076/2.7	2

NA = not applicable

TE92-3939

Table D-12.
Similar performance mini-van FCV.



Vehicle Data		Performance	
EPA classification	mini-van	Top speed (km/hr / mph)	145/90
Vehicle type	conceptual FCV	0 to 96.6 km/hr (60 mph)(sec)	cold 19.3
Curb weight (kg/lb)	1,805/3,972		warm 11.6
Test weight (kg/lb)	1,942/4,272	Gradeability (% grade)	
Wheelbase (cm/in)	279/109.8	Short term maximum negotiable	15.1%
Overall length (cm/in.)	493/194.2	Long term @ 96.6 km/hr	>6%
Overall width (cm/in.)	188/73.9	Range on FHDS (km/mi)	692/430
Frontal area (m^2/ft^2)	2.72/29.3	Start-up & drive-away time	<1 Sec
Drag coefficient (C_d)	0.33	Long term storage (days)	
Number of passengers	7	Ambient-normal start (21°C/70°F)	NA

EPA Volume Available		Energy Usage	
Passenger (m^3/ft^3)	4.15/146.5	Fuel economy (gasoline)	
Trunk/cargo (m^3/ft^3)	0.521/18.4	FHDS-highway (km/L / mpg)	9.09/19.5
Total volume (m^3/ft^3)	4.67/164.9	FUDS-city (km/L / mpg)	7.52/15.5
Fuel tank size (L/gal)	75.7/20.0	Composite energy (55/45) usage	
		(kW-hr/km)	0.536
		Energy usage compared to ICE	51%

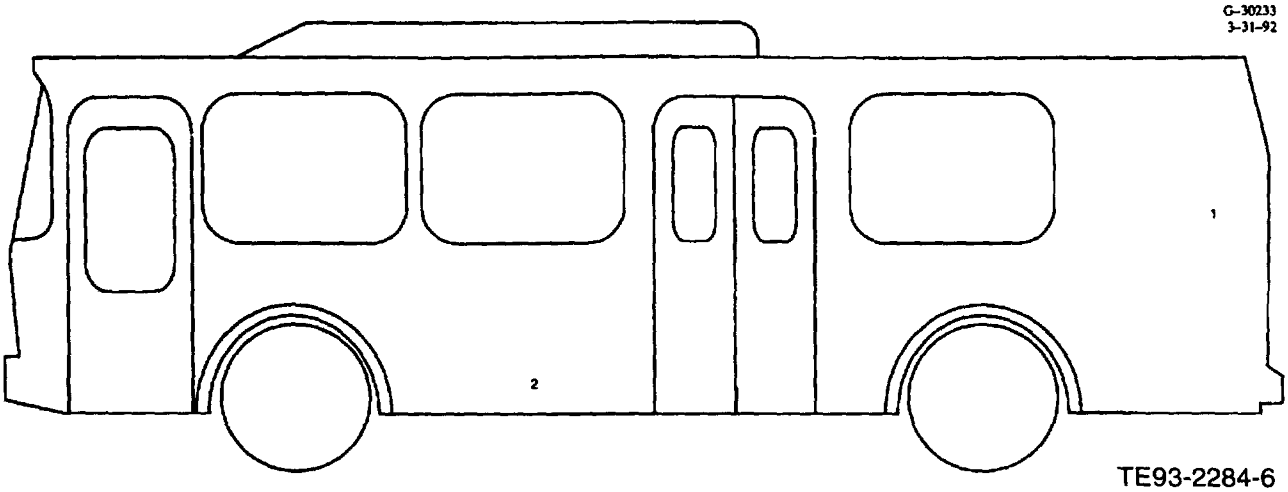
Components

	Rated power (kW)	Weight (kg/lb)	Volume (m^3/ft^3)	Location
Battery pack	67	291/641	0.136/4.8	4
Electric drive system	180	220/486	0.384/13.4	1
Electrochemical engine	60	244/537	0.365/12.9	4
ICE and transmission	NA	NA	NA	NA
Fuel tank	NA	72/158	0.076/2.7	2

NA = not applicable

TE92-3940

Table D-13.
Current production urban transit bus.



TE93-2284-6

Vehicle Data		**Performance**	
EPA classification	urban transit bus	Powerplant classification	low
Vehicle type	27 ft		
Curb weight (kg/lb)	8,181/18,000	Top speed (km/hr / mph)	97/60
Test weight (kg/lb)	10,909/24,000	Gradeability (% grade)	
Wheelbase (cm/in)	445/175	Short term maximum negotiable	16%
Overall length (cm/in.)	813/320	Start-up & drive-away time	<1 min
Overall width (cm/in.)	229/90	Long term storage (days)	
Frontal area (m^2/ft^2)	6.4/69	Ambient-Normal Start (21°C/70°F)	NA
Drag coefficient (C_d)	0.6		
Number of passengers	25		

EPA Volume Available		**Energy Usage**	
Passenger (m^3/ft^3)	29.1/1027	Fuel consumption at	
Trunk/cargo (m^3/ft^3)	NA	Rated load (diesel) (kg/hr/lb/hr)	16.7/36.8
Total volume (m^3/ft^3)	29.1/1027		
Fuel tank size (L/gal)	475/125		

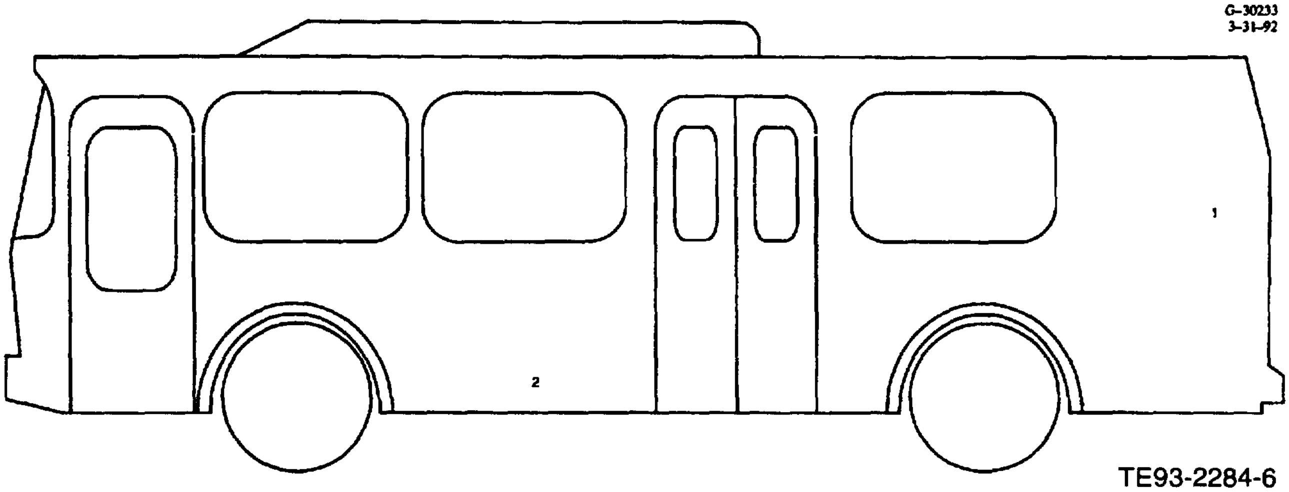
Components

	Rated power (kW)	Weight (kg/lb)	Volume (m^3/ft^3)	Location
Battery pack	NA	NA	NA	NA
Chopper	NA	NA	NA	NA
Electric motor	NA	NA	NA	NA
Electrochemical engine	NA	NA	NA	NA
ICE and transmission	134	NA	NA	1
Fuel tank	NA	165/364	0.181/6.4	2

NA = not applicable

TE92-3941

Table D-14.
Phosphoric acid electrochemical engine powered urban transit bus.



TE93-2284-6

Vehicle Data		Performance	
EPA classification	urban transit bus	Powerplant classification	low
Vehicle type	27 ft		
Curb weight (kg/lb)	8,648/19,025	Top speed (km/hr / mph)	76/47
Test weight (kg/lb)	10,148/22,325	Gradeability (% grade)	
Wheelbase (cm/in)	445/175	Short term maximum negotiable	16%
Overall length (cm/in.)	813/320	Start-up & drive-away time	33 min
Overall width (cm/in.)	229/90	Long term storage (days)	
Frontal area (m^2/ft^2)	6.4/69	Ambient-Normal Start (21°C/70°F)	NA
Drag coefficient (C_d)	.6		
Number of passengers	25		

EPA Volume Available		Energy Usage	
Passenger (m^3/ft^3)	27.0/954	Fuel consumption at	
Trunk/cargo (m^3/ft^3)	NA	Rated load (kg/hr/lb/hr)	20.5/45.2
Total volume (m^3/ft^3)	27.0/954		
Fuel tank size (L/gal)	475/125		

Components

	Rated power (kW)	Weight (kg/lb)	Volume (m^3/ft^3)	Location
Battery pack	60	568/1,250	0.263/9.3	2
Chopper	120	59/130	0.108/3.8	2
Electric motor	120	477/1,050	0.127/4.5	1
Electrochemical engine	50	820/1,804	1.13/40.0	1
ICE and transmission	NA	NA	NA	NA
Fuel tank	NA	165/364	0.181/6.4	2

NA = not applicable

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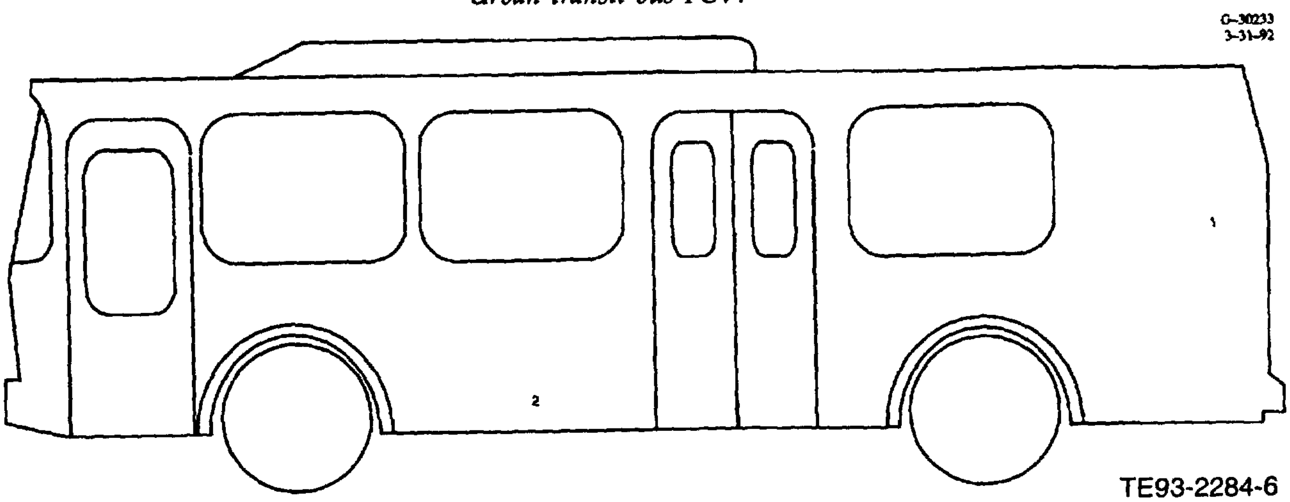
Table D-15.
Urban transit bus FCV.



TE93-2284-6

Vehicle Data		Performance	
EPA classification	urban transit bus	Powerplant classification	low
Vehicle type	27 ft		
Curb weight (kg/lb)	8,045/17,699	Top speed (km/hr / mph)	76/47
Test weight (kg/lb)	9,545/20,999	Gradeability (% grade)	
Wheelbase (cm/in)	445/175	Short term maximum negotiable	16%
Overall length (cm/in.)	813/320	Start-up & drive-away time	5.0 min
Overall width (cm/in.)	229/90	Long term storage (days)	
Frontal area (m^2/ft^2)	6.4/69	Ambient-Normal Start (21°C/70°F)	NA
Drag coefficient (C_d)	0.6		
Number of passengers	25		

EPA Volume Available		Energy Usage	
Passenger (m^3/ft^3)	27.0/954	Fuel consumption at	
Trunk/cargo (m^3/ft^3)	NA	Rated load (kg/hr/lb/hr)	15.4/34.2
Total volume (m^3/ft^3)	27.0/954		
Fuel tank size (L/gal)	475/125		

Components

	Rated power (kW)	Weight (kg/lb)	Volume (m^3/ft^3)	Location
Battery pack	60	568/1,250	0.263/9.3	2
Chopper	120	59/130	0.108/3.8	2
Electric motor	120	477/1,050	0.127/4.5	1
Electrochemical engine	50	217/477	0.306/10.8	1
ICE and transmission	NA	NA	NA	NA
Fuel tank	NA	165/364	0.181/6.4	2

NA = not applicable

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